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Fig. 1. G. I. Matveychuk taking meteorological observations at Scientific Station North Pole 3 in the autumn of 1954.

THE SOVIET EXPEDITION TO THE CENTRAL ARCTIC, 1954

Clifford J. Webster

In 1932 the Chief Administration of the Northern Sea Route (G.U.S.M.P.) was founded by the Soviet government to develop an arctic shipping lane between the Atlantic and Pacific oceans. Almost immediately, the Russians realized that detailed knowledge of the Central Arctic Basin, particularly as regards ice, weather, and hydrography, was essential to the success of this route. For three decades the G.U.S.M.P. has been carrying out a continuous program of research. This has taken the form of observations from a large net of polar stations, from ships, from drifting ice stations, and through aerial reconnaissance. The most important and spectacular aspect of this program has been the penetration of the Central Arctic Basin. This has involved landings by aircraft on unprepared sea ice, the mounting of stations on drifting ice, and the establishment of a system of aerial ice and weather reconnaissance.

Previous expeditions

Before the outbreak of the Second World War the G.U.S.M.P. had amassed a considerable experience in the mounting of stations on drifting ice and in the necessary air support. The usefulness of drift expeditions had been demonstrated by Nansen's expedition in the *Fram* in 1893, and by Amundsen's drift in the *Maud* in 1922. Indeed, when the G.U.S.M.P. was founded the Russians owed the whole of their data on the Central Arctic Basin to Nansen's work in the *Fram*. They lost no time in an effort to build on his work. Between 1935 and 1937 the icebreaker *Sadko* carried out three annual drifts in the northern parts of the Kara and Laptev seas. The Russians' first effort to penetrate the Central Arctic Basin was made in 1937 by the Papanin North Pole Drift expedition. During the course of nine months, this group of four men drifted south on an ice floe from the north pole to a point off the east coast of Greenland. Their station was established by four 4-engine aircraft which carried out landings on unprepared sea ice and delivered nine tons of freight. The Papanin group contributed data which in some respects radically altered previous notions of the region. In the same year, the icebreaker *Sedov* drifted from the Laptev Sea across the Western Arctic Basin; but, being an extemporized drift, its results were less satisfactory. In 1939 the Russians felt that they still needed data from the region north of the *Sedov* drift, and, in particular, north of the coastal waters of their Eastern Arctic.[1] In that year,

[1]In the Soviet concept, Mys Chelyuskin marks the approximate boundary between the Western and Eastern Sectors of the Soviet arctic coast. In this account the terms Western Arctic and Eastern Arctic refer to the Russian sectors.

a veteran arctic pilot, I. I. Cherevichnyy, proposed an expedition in 1940 to that region which lies between 150°E. and 70°W., and which contains the so-called "Pole of relative inaccessibility". This was not done until 1941. On this occasion, a 4-engine aircraft, flying north from Ostrov Vrangelya, carried out three landings on the unprepared sea ice in April in the vicinity of 80°N. Only a few days were spent at each station, however, and serious work had still to be attempted.

Drift expeditionary work was interrupted by the Second World War, but was resumed soon after its conclusion. As part of its Fourth (postwar) Five Year Plan, the Arctic Scientific Research Institute undertook to complete the comprehensive mapping of the Arctic Basin, to intensify its studies of ice movement, and to adopt the use of automatic meteorological stations. The value of the latter had been recognized at the close of the Papanin expedition. In 1947 V. S. Antonov, Assistant Director of the Arctic Institute, announced that an automatic weather station had been built, and had been successfully used as an arctic drift station. Prof. Ya. Ya. Gakkel' was one of the designers. It was foreseen that radio buoys, intended for the study of the propagation of radio waves in the Arctic, might also be useful for the study of ice movements. At the same time, it was announced that Simonov had perfected a "drift-graph" for charting the speed and direction of drift and the depth of the sea bottom. A portable instrument for measuring terrestrial magnetism was also produced. On this basis, drift expeditions began again, the main effort once more being in the relatively inaccessible area of the Eastern Arctic.

In April 1947 an expedition was mounted from Ostrov Kotel'nyy. Stations were set up on the ice at 80°30N., 150°00E., at 86°30N., 157°00E., and at 80°15N., 177°00E. Daily flights were made from these to surrounding points, where from one to three days were spent taking observations. At the same time, three aircraft landed a party of scientists at the pole. This party allegedly completed its program in two days; but evacuation was rendered necessary and difficult by a crack which split their floe and they had to abandon their fuel reserves to permit a short take-off. A similar expedition, led by Prof. Ya. Ya. Gakkel', was active in 1948–9. This party made observations at more than two hundred sites, and is credited with the discovery of a great submarine range which extends across the Central Arctic Basin from the Novosibirskiye Ostrova toward Greenland and Ellesmere Island. This has been named after Lomonosov, the celebrated Russian *savant* of the eighteenth century, whom the Russians regard as the founder of arctic oceanography. The results pointed to the need for systematic study of seasonal variations in the climate, of magnetic phenomena, and for a more detailed study of several regions. In April 1950 a further expedition was mounted in the Eastern Arctic at 76°02N., 166°30W. This party, led by M. M. Somov, drifted until it was evacuated in April 1951 at 81°45N., 162°20W. An indication of its scale lies in the report that it was equipped with a cross-country vehicle (probably a GAZ-67), and received, after six months on the ice, some twenty tons of re-supply. This expedition assembled a considerable body of data on the "Pole of relative inaccessibility".

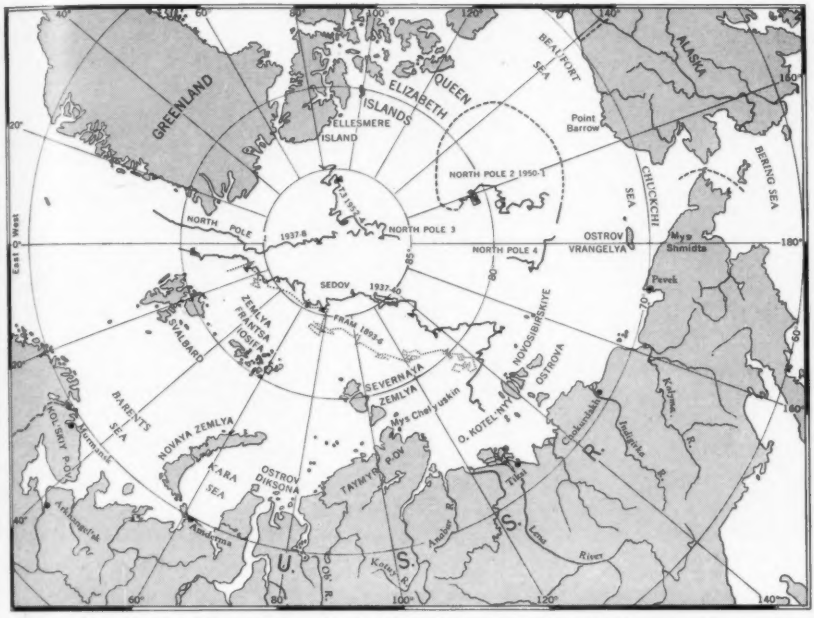


Fig. 2. Tracks of drift expeditions in the Central Arctic Basin, 1893–August 1954, as given in *Izvest. Akad. Nauk S.S.S.R., Ser. Geogr.* No. 5, 1954, p. 5.

The Papanin expedition is now known as "Scientific Station North Pole 1". The Somov expedition, apparently outranking the expeditions of 1947–9, has been designated "Scientific Station North Pole 2".

Very soon after the Revolution, the Soviet arctic authorities learned the value of the aircraft for communications, logistics, and survey in the Arctic. By the mid-'thirties, the air services of the G.U.S.M.P. had been given the specific task of aerial ice reconnaissance. By the outbreak of war, the outlines of a systematic method had crystallized. This took the form of regular flights over the coastal seas to support short-term ice forecasts, and of pre- and post-seasonal flights over the Central Arctic Basin to support long-term ice forecasts. Construction of a series of necessary coastal air bases, called for in the Third Five Year Plan, got under way in 1941–2. Unlike drift expeditionary work, this air activity was not interrupted by the war, and flights were made annually between 1940 and 1945. V. I. Akkuratov claims that an ice reconnaissance flight in October 1945 from Mys Chelyuskin to Chokurdakh via the north pole pioneered such operations in the winter darkness and led to the introduction of new techniques for landings on the pack. In the decade ending in 1946, when four flights were made into the Central Arctic Basin, at least thirty major flights had been made into this region, and a number of landings on unprepared sea ice had been carried out by heavily-laden 4-engine aircraft in mounting and supporting drift expeditions.

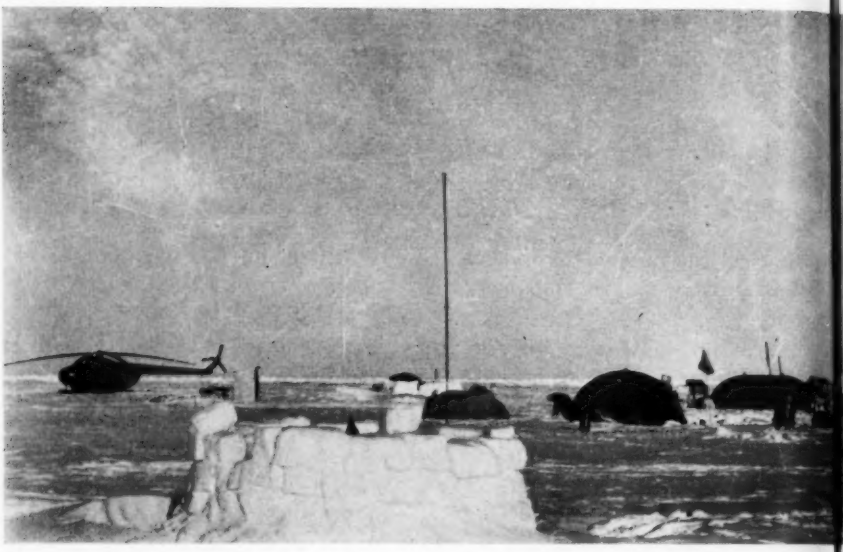


Fig. 3. Scientific

All the expeditions between 1937 and 1950 carried out a complex program of investigations. The work included measurements of the depth of the ocean; the collection of bottom samples for the study of the relief and geological history of the sea bed; measurement of water temperatures at various depths and the collection of water samples for the study of its origin and distribution through chemical analysis; the collection of plankton specimens; measurement of currents; readings of the temperature of the ice, of the layer of air overlying the ice, and of the intensity of solar radiation, to study the exchange of heat between the ocean and the atmosphere; frequent astronomical fixes to determine the drift of ice over large expanses of the ocean; regular meteorological and upper air observations; aerial ice reconnaissance; geomagnetic observations; gravimetric observations, and the study of problems of geodesy and geology.

The 1954 expedition

Early in 1954 the Soviet government undertook a program of research in the Central Arctic Basin which is the largest attempted thus far. The intention, which has been frequently repeated in the press, is to complete the exploration of the region, in order to ensure the maximum development of the Northern Sea Route. In practice, this means an effort to make sea and air navigation in the Arctic more secure; and this means, essentially, the systematic collection of all the data which are needed to improve ice and weather forecasts. A major feature of the current program is therefore the decision to attempt observations on a broader and long-term basis, instead of

Photo: Sovfoto

n Pole 3, July 1954.

on a sporadic "expeditionary" basis. The following account is based on published Russian material and merely seeks to report results claimed and to outline Soviet theories.

The plan adopted for the 1954 expedition called for operations to be mounted jointly by the Academy of Sciences and the G.U.S.M.P. throughout that area of the Arctic Basin north of the U.S.S.R., and consisted of four parts:

A drift station under A. F. Treshnikov to be mounted in the Central Arctic by an air detachment under I. S. Kotov from bases at Ostrov Diksona, Mys Chelyuskin, and other coastal points.

A drift station under Ye. I. Tolstikov to be mounted in the Eastern Arctic by an air detachment under M. A. Titlov from bases at Tiksi, Pevek, and probably Mys Shmidta.

"*The High Latitudes Air expedition*" *under M. Ye. Ostrekin* consisting of two groups, one to be landed at the north pole by an air detachment under I. I. Cherevichnyy, flying from Ostrov Diksona, and using transit bases on Zemlya Frantsa Iosifa and on the sea ice, and the other to be flown by V. I. Maslennikov to the outer edge of the continental shelf in the northern Chukchi Sea. The work of these groups was to be coordinated with that of the drift stations and of the regular polar stations.

Regular flights by one or more "flying laboratories" along almost the whole periphery of the area of the expedition, during which meteorological and ice observations were to be made.

Freight for the whole expedition was concentrated at Ostrov Diksona, the main headquarters, during March 1954. From this point, supplies for the drift station in the Eastern Arctic were delivered eastward, probably to Mys

Shmidta. During approximately the last week of March 1954, the main party took off from a field south of Moscow in a group of aircraft consisting of a PE-8 and a number of IL-12 and LI-2 aircraft. They flew via Arkhangel'sk and probably Amderma to Ostrov Diksona. The balance of the party, containing the personnel for the drift station in the Central Arctic, flew somewhat later from Leningrad to Ostrov Diksona.

Scientific Stations North Pole 3 and 4

The most ambitious element in the 1954 program has been the mounting of two drift stations on the sea ice. That in the Central Arctic, under Treshnikov, has been designated "Scientific Station North Pole 3", and that in the Eastern Arctic, under Tolstikov, "Scientific Station North Pole 4".

The selection of a floe for "North Pole 3" seems to have been somewhat difficult. It appears that a separate transit base was necessary and that this was located north of Severnaya Zemlya. The first floe selected by Kotov to the north of this base proved unsatisfactory, and another was found 15 km. farther to the north. This, too, was unsuitable for heavy aircraft, and Kotov was forced to land some 7–9 km. to the southwest. It appears that freight and personnel had to be ferried to the selected floe by a helicopter and an AN-2 aircraft. Eight days after this floe had been located, North Pole 3 was set up in April, some 1,300 km. from the mainland at 86°00N., 175°45W.

Complicated ice conditions north of Ostrov Vrangelya and cloudy weather also impeded the selection of a landing site for "North Pole 4". It was not until eight days after the expedition left Moscow, and probably at the end of March, that a transit base was established some 600 km. north of Mys Shmidta. After a further four days of reconnaissance from this base, a floe suitable for a drift station was found. One week after its transit base had been set up, North Pole 4 was established in April about 100 km. farther north, at 75°48N., 175°25W. The personnel for the drift station were flown out by Titlov.

Each station is equipped with living and working quarters in the form of tents and prefabricated huts. The huts consist of panels made of plywood and wood pulp which is said to be 4–5 times lighter than wood and to possess insulating qualities 3 times superior. The tents, which were originally designed by S. A. Shaposhnikov for use by the "mobile groups" of previous expeditions, are modelled on the Chukchi *yarang*, and consist of a collapsible framework of duralumin tubes, covered with two layers of canvas. These are separated by an air space and the outer layer is dark, the inner white. The basic unit appears to be a hemispherical tent. This can be increased in size by elongation, i.e., the hemisphere is divided into two parts, between which a semi-cylindrical extension is inserted. The floor consists of three layers: a bottom waterproof fabric, then a layer of reindeer hides, and finally a top layer of plywood sheets. The tents seem to be used primarily as working quarters. The huts, which are delivered in seventeen sections, consist of living room, kitchen, and hall, accommodate four men, and are mounted on runners. They weigh 700–750 kg., and can be moved by the occupants, if necessary. Good pictures of these huts have only recently been released in

Photo: Y. Ryumkin

Fig. 4. Two prefabricated huts at North Pole 3, which have been joined together, autumn 1954.

Photo: Y. Ryumkin

Fig. 5. Interior of the mess-hut at North Pole 3, showing L. Razbash setting the table. In the left background the "wall newspaper" can be seen; in the right background the board shows the chess game being played between North Pole 3 and 4.

Photo: Sovfoto

Fig. 6. The KD-35 tractor at North Pole 3, August 1954.

Photo: Soviet Union

Fig. 7. V. A. Shamont'yev taking a depth sounding at North Pole 3.

Photo: Soviet Union

Fig. 8. A. D. Malkov with the pyrheliometer at North Pole 3.

Photo: Y. Ryumkin

Fig. 9. Interior of the radio station at North Pole 3, showing, left and right, K. M. Kurko and L. Razbash, radio operators, and centre, A. F. Treshnikov, leader of the ice station.

the press although TASS stated on 29 July 1954 that the Sovetskiy Timber Works was completing the second consignment. Snow houses also appear to have been built at each station. Stoves of "special construction" have been supplied for heating purposes. Cooking is done on ranges using liquid gas, probably propane. Each station has a mess, a bath, a library, and a cinema. At least North Pole 3 has an upright piano.

No radically new instrumentation has been revealed in the Soviet press. Some unexplained modifications have been made to the dip circle. The Stevenson screens are mounted at the unusual height of 6–8 feet; this may merely reflect the use of a standard quadrupod for areas of heavy snow and ground drift. Radio aerials are of ordinary design, and communications have frequently been disrupted when these have been broken by gales and icing. The radiosonde equipment appears to be normal. The press states that a special plant has been provided to generate hydrogen locally for the balloons. At the site of radiosonde observations, a theodolite has been shown. In clear weather, at such latitudes, this instrument may be useful for observing wind speeds at relatively great heights. There is no evidence of radio or radar for this purpose. At North Pole 3 an instrument resembling a nephoscope has been shown. The pyrheliometer has been photographed with as many as three black discs attached. At least one type of hydrological winch is power-driven, and is fitted with 10,000 m. of steel cable. The fact that only a light, short, manual ice auger has been shown probably indicates that holes for soundings are blasted, rather than bored, through the ice. One cylindrical

Photo: Y. Ryumkin

Fig. 10. Transit base for North Pole 3, showing the arrival during the polar night of an LI-2 aircraft. The bottles in the foreground contain gas for heating purposes. The cross-country GAZ-69 automobile will transfer passengers and freight to the ice station over a route cleared by a tractor.

metallic case, used by the oceanographers, appears to be a type of echo sounder, and may be of original design.

Each station has a large helicopter, possibly an AN-2 aircraft, a GAZ-69 automobile, and a KD-35 tractor (28 d.b.h.p., about 4 tons weight), fitted with a blade, which has been used to develop and maintain their airstrips. With this equipment, alternate sites have been established and provisioned on each floe.

At these stations oceanographical, hydrographical, meteorological, actinometric, magnetic, and geophysical observations are being taken. From both stations detachments are flying out by helicopter to take similar observations on the ice at a distance from the main base. A party from North Pole 3 has worked as far as 100 km. to the north of its station. Sea ice conditions are being constantly studied, including those changes in its mechanical properties

which are associated with increasing age. Probably in July 1954, a delegation of the Academy of Sciences spent two weeks at the drift stations. The purpose of the visit was to discuss the enlargement of the scientific program in the fields of geology, geomorphology, and hydrobiology. It is apparently desired to enlarge the collection of data on the relief of the sea bottom and on the formation and age of sea ice. It is hoped that the results will yield more precise knowledge of the age of the Arctic Basin.

Both drift stations are equipped with electric light, radio, and telephone. Radio communication is constantly maintained between each station and the mainland. Meteorological observations are broadcast eight times daily. These give surface pressure, air temperature, wind direction and speed, height and type of cloud, and precipitation. Upper air observations are also reported. One daily broadcast gives depth, bottom samples, water temperatures at various levels, and the location of the oceanographic station. It is not known how many other weather stations have been established in conjunction with the expedition. The press has not stated that automatic weather stations play a role in the present program.

Both drift stations are obviously intended to function over a period of many months and possibly of several years. The leader of North Pole 3 has stated that his party will spend the winter of 1954–5 in the Central Arctic. The problem of re-supply as well as of air communications in general, has therefore entailed the development of airstrips. The press has referred to the delivery to both stations of mail, passengers, and of fresh provisions; but no pictures of airstrips or of heavy aircraft at either station have been released. Only helicopters have been shown at North Pole 3 and 4. The press has shown a photograph of Treshnikov and his colleagues smoothing out an airstrip with shovels; and the "wall newspaper" published at his station has contained an article urging the station complement to improve their strip. These may simply be references to a local landing site for the helicopter and the AN-2. It is possible that at least two, and perhaps several, transit bases are still in use, and that two of these are the sites of the major air terminals serving the drift stations.

High Latitudes Air expedition

The "High Latitudes Air expedition" under the geophysicist Ostrekin was given the task of determining the precise location of the Lomonosov Range in the vicinity of the north pole. It was also required to repeat some of the magnetic observations made in this region in 1937 by Papanin. The press has said nothing about the nature of the work in the northern Chukchi Sea, but this possibly involved investigation of the floe vacated by Somov's party in 1951. Ostrekin's party seems to have used at least two IL-12 aircraft, both of which appear to have made landings on unprepared sea ice, a large helicopter, and an AN-2 biplane. A transit base was established on Zemlya Frantsa Iosifa. The use of light aircraft supports an inference from the press that more than one transit base was necessary on the sea ice; it is believed that at least two were required, one to the north, and the other to the south of the

Photo: Ogonyek

Fig. 11. Interior of the flag-aircraft of the Ostrekin expedition to the north pole, showing, left to right, M. Ye. Ostrekin, V. F. Burkhanov, I. I. Cherevichnyy, and D. I. Shcherbakov; standing, V. P. Padalko, a veteran arctic navigator.

Photo: Ogonyek

Fig. 12. Ye. I. Tolstikov, leader of Scientific Station North Pole 4.

archipelago. From the site or sites where they landed near the pole, this party sent out air-lifted detachments to work at distances of 40–50 km. Several dozen landings seem to have been made at various points around the pole. Observations were taken by the detachments at each position over varying periods. The Ostrekin party was to complete its work in about a month. In July 1954 the Soviet government announced that it was back in Moscow.

Meteorological flights

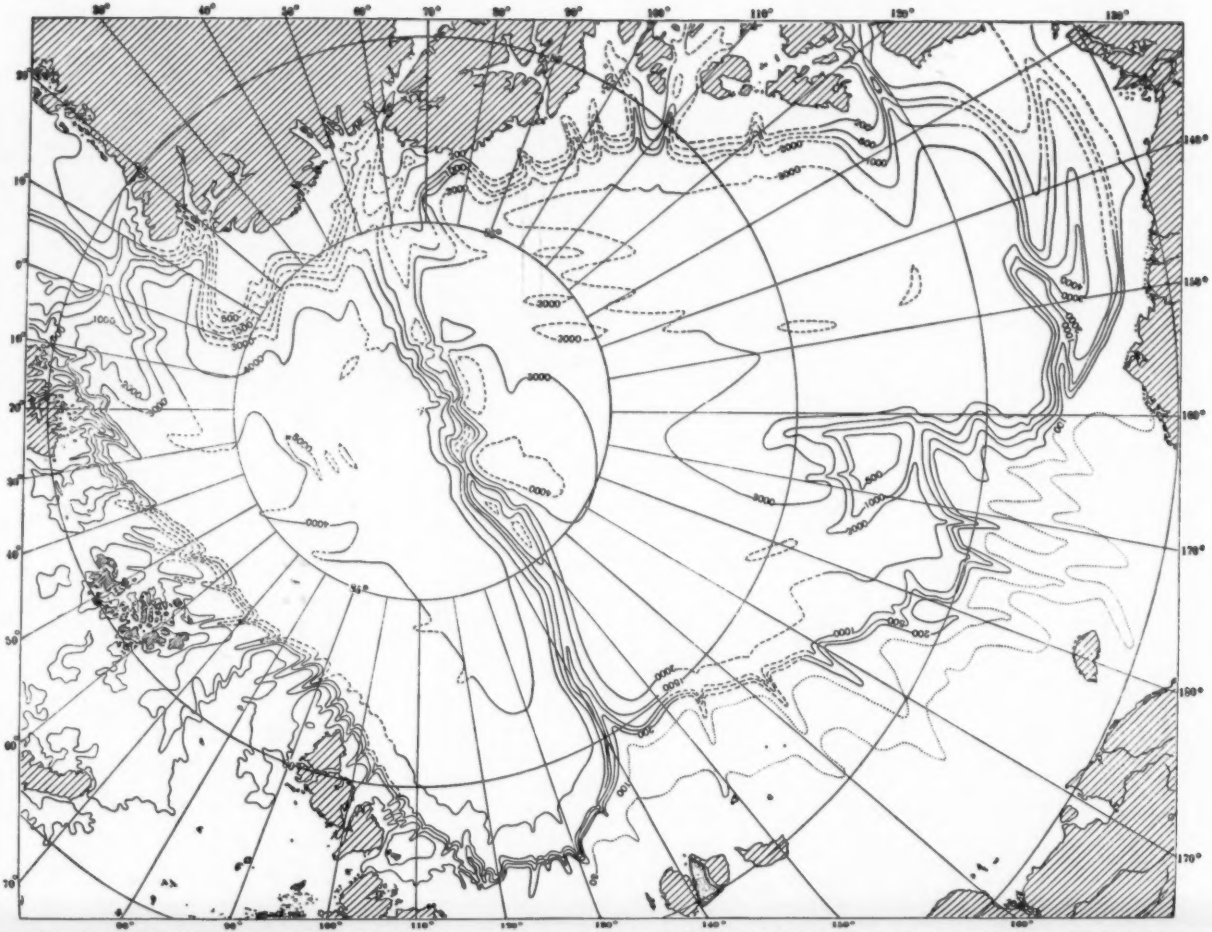
The Soviet press has said little of the fourth element of the 1954 expedition. It has merely referred to one or more "flying laboratories" which have carried out flights over the Central Arctic Basin. Some of these have reached the north pole.

Personnel connected with the expeditions

Many eminent arctic specialists are engaged in the current program. The Academy of Sciences is represented by Academician D. I. Shcherbakov, Secretary of its Geological-Geographical Section, and by the Corresponding Member Ye. K. Federov. The latter was the geophysicist on the Papanin expedition in 1937. V. F. Burkhanov, head of the Main Administration of the Northern Sea Route, is director of the 1954 expedition to the Central Arctic. Suyumov is Scientific Secretary of the whole expedition. The known senior officers of the expedition include the oceanographers Professors N. N. Zubov and Ya. Ya. Gakkel', the eminent geographer and specialist in hydrometeorology, G. A. Ushakov, and M. M. Somov, Deputy Director of the Arctic Institute, who led the drift expedition of 1950–1. Several veteran arctic pilots and navigators have been active. I. Mazuruk flew the flag aircraft, which was probably navigated by V. I. Akkuratov. M. A. Titlov flew in the party for North Pole 4, I. S. Kotov flew in that for North Pole 3. In addition, M. V. Vodop'yanov and Alekseyev appear to have served as advisers. M. I. Kozlov, V. M. Zadkov, and I. G. Bakhtinov were also active.

The press has announced the names of seventeen members of North Pole 3. These are A. F. Treshnikov, oceanographer, formerly with the Arctic Institute, veteran of the drifts of 1948–50, leader; V. A. Shamont'yev, hydrologist, deputy leader and Party organizer; A. F. Babenko, helicopter pilot; A. I. Dimitr'yev, hydrologist; V. G. Kanaki, veteran arctic meteorologist, probably from the Arctic Institute, director of scientific work; M. S. Komarov, mechanic; K. M. Kurko, radio operator; A. D. Malkov, meteorologist; G. I. Matveychuk, in charge of the meteorological detachment; G. A. Ponomarenko, hydrologist; N. Ye. Popkov, meteorologist; P. P. Poslavskiy, meteorologist with twenty-three years' arctic experience; I. M. Sharikov, hydrometeorologist and cook; L. Razbash, radio operator; I. Tsigel'nitskiy, engineer; V. Volovich, medical officer; and Ye. Yatsun, photographer and cinema operator.

The press has said less about North Pole 4, and only ten names have been released: Ye. I. Tolstikov, meteorologist, leader; A. G. Dralkin, hydrologist, deputy leader; M. I. Ivanov; M. Izvekov, hydrometeorologist; Paleyev, medical officer; Shirkov; Shutyayev, mechanic; Vasil'chenko, tractor driver; I. V. Zavedeyev, radio operator; and M. Zinchenko.



It is possible that as many as twenty to thirty persons may form the permanent complement at each drift station. The majority are between the ages of 22 and 35, and a third have spent an average of over 12 years in the Arctic. It is not known how many persons have visited the drift stations. The delegation from the Academy of Sciences which V. G. Kort, Director of the Institute of Oceanology, reported on 29 July 1954 had spent two weeks at the stations, probably included the oceanographer Zenkevich, the ice specialist P. A. Shumsky, the microbiologist A. E. Kriss, Chief of the Marine Microbiology Department of the Institute of Microbiology, and one Yurin from Moscow University.

Nothing is known about the personnel of the Cherevichnyy-Ostrekin party which landed at the north pole, nor about the detachment which was flown by Maslennikov to the northern Chukchi Sea.

Dolgin, who directs the special flights over the Central Arctic Basin is a meteorologist. P. A. Gordienko and N. A. Volkov, his assistants are, respectively, an ice specialist, and an officer of the Arctic Institute.

Scientific results

Scientific results of the work done in the Central Arctic Basin since 1947 have not yet been released in detail. A number of press reports since February 1954 have, however, provided an outline of the results obtained since 1948, but little has been revealed of the results of the present expedition.

Oceanography and hydrography

Since the discovery of the Lomonosov Range by Prof. Gakkel"s expedition in 1948, oceanographical and hydrographical studies have been principally directed towards an understanding of the implications of this range.

It has been established that the range has elevations of 2,500 to 3,000 m., and it is claimed that the Ostrekin party has confirmed that it stretches from the Novosibirskiye Ostrova across the north pole to Greenland and Ellesmere Island, a distance of 1,800 km. It thus divides the Arctic Ocean into two major basins. In some places its peaks rise to 954 m. from the surface; its slopes are steep and saddles of a depth of 1,500–1,600 m. and spurs are characteristic. Preliminary data indicate that the range was formed in Mesozoic or Tertiary times, and originally rose above the surface of the Arctic Ocean. It has been established that the floor of the Arctic Ocean is complex, and, like that of the Mediterranean, has been formed by the rising and sinking of the earth's crust. A number of lesser elevations divide the ocean into a series of deeps. The widest and the deepest lies north of the Greenland, Barents, Kara, and Laptev seas. This extends along the Lomonosov Range, and is bounded on the south, between Svalbard and Greenland, by the Nansen Sill and by the continental shelf of the Barents and Kara seas. Its maximum depth is over 5,220 m., at which reading the *Sedov* did not find bottom. A smaller deep is located on the opposite side of the Lomonosov Range. This is roughly oval in shape, and runs north from the 85th parallel between the meridians of 160°E. and 90°W. In this region, depths of up to 4,000 m. have been found. To the

south, this deep is bounded by a great underwater plateau, with depths of 2,300–2,800 m. A third deep, lying north of the Chukchi and Beaufort seas, has depths up to 3,820 m. This deep is linked by a narrow strait with the smaller deep of the Beaufort Sea, which has depths of up to 4,689 m. Evidently, in addition to the Lomonosov Range, there exists a further and older folded system of approximately parallel ranges which intersect the Lomonosov Range at angles of 60 to 120 degrees. Another series of elevations runs from the Chukchi Sea to the region of the Nansen Sill and joins Svalbard and Greenland. The Russians draw attention to the fact that the Lomonosov Range lies parallel to the continental slope of the Barents and Kara seas, along the thrust line of which there took place, when the Lomonosov Range was formed, a tectonic dislocation of the earth's crust. The older system of folds evidently forms a chain of mountains and crests which parallel the North American continental shelf. Where these systems intersect, very high mountains exist.

The boundaries of the continental shelves have been more exactly defined. North of Bering Strait the shelf forms a huge submarine peninsula which reaches 80°N., i.e., practically 600 km. farther north than was previously thought. The Somov expedition drifted over this peninsula three times, and found pebbles at all depths. It has been established that the Eurasian continental shelf slopes off much more steeply than was previously imagined. North of the Laptev Sea the angle of descent reaches as much as 18 degrees. The Russians state that the depth of 5,440 m., measured by Wilkins in 1927 at 77°46N., 175°00W., on which doubt had been cast by the 1941 expedition, has been shown to be erroneous. Depths of 2,048 m. and of 1,928 m. have been recorded 11 km. north and 28 km. northeast of this point, respectively.

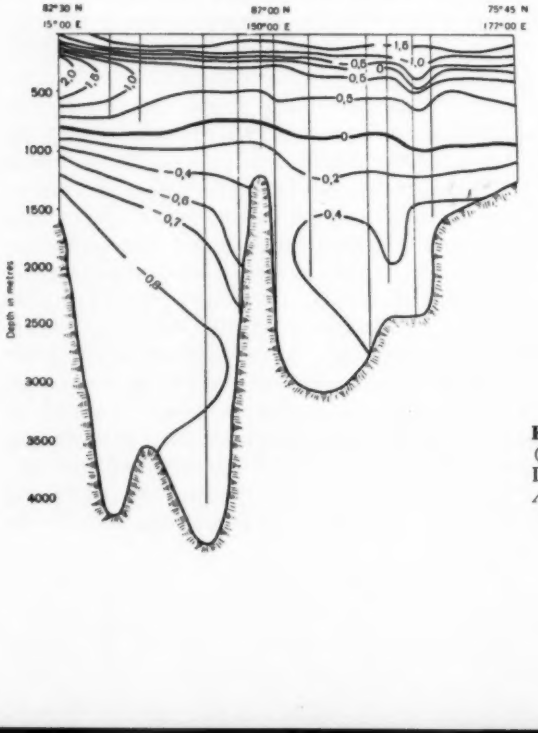


Fig. 14. Water temperatures (°C) on a section across the Lomonosov Range, from *Izvest. Akad. Nauk S.S.S.R., Ser. Geogr.* No. 5, 1954, p. 8.

Hydrological studies have also confirmed the existence of two major basins separated by the Lomonosov Range. Waters at the bottom of the Central Arctic Basin are Atlantic in origin. Cold bottom waters spread north from the Greenland Sea, and reach the foot of the Lomonosov Range, but do not cross it. These are colder than the waters at great depth on the other side of the range. But warm Atlantic waters, with positive temperatures, have been found below the cold surface layers in all parts of the Arctic Ocean. Waters from the Pacific penetrate considerably farther north from Bering Strait than was previously known.[1]

The development and migration of zooplankton and phytoplankton has been studied at great depths on a year-round basis. Large quantities and many varieties of copepoda have been found, at depths of up to 3,400 m. Specimens taken in the Eastern Arctic in 1948 included types not previously known. These findings are hailed as upsetting the theories of the scarcity of plankton in the Arctic Ocean and of the relative uniformity of benthic fauna throughout the world. In the Eastern Basin, between 160°E. and 60°W., the waters near the bottom are different, and the fauna is poor. In this region, the richest collections were made at a depth of 100 m., where a current from the Pacific has been identified.

Wildlife

The presence of polar bear, fox, seal, and of flocks of ducks, gulls, and snow bunting has been reported at distances of over 1,000 km. from the mainland.

Ice

The relief of the bottom has an important effect on the distribution and drift of ice through its effect on the water circulation at all levels. While emphasizing this, the Russians claim that they have confirmed their earlier conclusion that the general drift in the Central Arctic depends on the predominant isobaric pattern. West of the Lomonosov Range, the drift of the sea ice is anti-clockwise, east of the range, it is clockwise. In the west, the ice is mainly two to three years old, is frequently carried into the Barents and Kara seas, and is frequently renewed. There may, however, be considerable periods when the ice follows a closed trajectory; the radius of this trajectory varies greatly, from a small line subtending the northern part of the Laptev Sea, to a very long diameter which extends across almost the entire Western Basin of the Arctic Ocean. In the east, the ice is thicker, older, and far less mobile; regions of dynamism and of quiet have been distinguished. The line of drift on one side of the Lomonosov Range is independent of that on the other; on neither side is the line of drift constant. Ice from east of the range occasionally moves off at a tangent to join the movement toward the North Atlantic; but the actual discharge of ice into the Greenland Sea is very irregular. The Russians claim that, during the southward drift, the rate of

[1]Recent work done from the Scripps Institution of Oceanography has also led to the same conclusion.

degradation exceeds that of accretion; during the northward drift, the reverse relationship obtains. Thus the sea ice is periodically rejuvenated—about once every four to five years. During the drift northward from Ostrov Vrangelya, the pack tends to loosen up. The speed of drift is generally about 1–1.5 miles in 24 hours. The slackening of the ice, consequent on a change of weather, may produce drift velocities of up to 1 mile per hour. Normally, the average speed of drift is greatest from February to April, and least from July to September.

It is claimed that ice conditions east of the Lomonosov Range are the key to ice conditions along the entire Northern Sea Route, and that the interaction of the reverse drifts on each side of this range account for the so-called Ayon and Taymyr "ice-massifs", or ice clusters, which lie athwart the Northern Sea Route. Within the crude outlines of this highly generalized picture, the Russians admit that the drift is far more complex, and the ice far older, than they had originally appreciated. The basic laws governing drift are not yet known, nor are the laws governing seasonal changes in the drift. It is hoped that a major achievement of North Pole 4 will be the discovery of a new and fundamental "ice current".

The positions of the drift stations now functioning have been announced as follows:

	April '54	15 July '54	10 August '54	15 Sept. '54
North Pole 3	86°00N., 175°45W.	88°02N., 151°40W.	89°30N., 140°00W.	89°34N., 54°30W.
North Pole 4	75°48N., 175°25W.	77°22N., 174°20E.	78°00N., 174°00E.	79°40N., 178°27E.

It is reported that North Pole 2 was abandoned in April 1951 at 81°45N., 162°20W. and that this floe, by June 1954, had drifted in a clockwise direction to 75°40N., 175°05W. At this point, a party was again landed to carry out detailed observations. It is possible that this was the group from the High Latitudes Air expedition which was flown into the Chukchi Sea by Maslennikov.

Although both drift stations have been mounted on floes of old pack ice, a good deal has been published since March 1954 about ice islands. An early release claimed that these do not move with the pack, but, being affected by deep, subsurface currents, follow an independent trajectory. Yet the course which the Russians indicate coincides generally with that recorded by Canadian and American observers and with that indicated by the Russians for the pack itself in the Eastern Basin of the Arctic Ocean. Similarly, Burkhanov has made an effort to refute the notion of their stability, but Zubov has emphasized their age and solidity; a late release has simply stated that some ice islands have been seen to break up into relatively small fragments. Another writer has spoken of their drift as continuing over many years or even centuries. Ice islands are hailed as the explanation of land formations reported by earlier explorers but never found again, such as Sannikov Land and Andreyev Land. The Russians began by claiming that they had sighted ice islands before the West, attributing the first description to Admiral Makarov at the turn of the century, and claiming sightings by arctic aviators since 1939. A recent and more serious article simply states that the Russians first saw these in 1946. It is reported that the icebreaker *Mikoyan* tied up beside an ice island in 1947 to the north of Ostrov Vrangelya, and disembarked a party to carry out

detailed studies. Ice islands are described as varying in shape, attaining sizes of 600 to 700 sq. km., and a maximum elevation above the sea of 10 to 12 m. The largest,[1] found in April 1948 at 82°30N., 173°00E., measured 28 by 32 km.

A study has been made of the process of the break-up of floating sea ice, and of the formation of cracks, leads, and open patches. The thawing of sea ice under the influence of the sun's rays has been studied on the under as well as the upper surface of the pack. It has been noticed that cracks occasionally form in the pack which do not alter their direction as they cross fields of differing thickness and age, even those composed of very old ice. The formation of such fissures is connected with the passage of waves in the water layers immediately below the ice. It has been established that the break-up and movement of the ice is very closely connected with changes in synoptic conditions; these processes are intensified by the penetration of cyclones into the Arctic.

Meteorology

In recent years meteorological observations have embraced almost the whole of the Central Arctic Basin. These have destroyed the older idea of a permanent high pressure area[2] and of predominantly anticyclonic weather in the region. The work of North Pole 1 showed that cyclones, often quite intense, and usually accompanied by cloudy weather and precipitation, penetrate the region. Cyclonic activity is characteristic of the whole cold period of the year. A relatively large number of deep cyclones have been encountered by various "mobile groups". The spring is characterized by complex weather patterns, and an intensive movement of warm air masses toward the pole. Over the coastal seas, cyclones are frequently active, with well developed warm and cold fronts. As a rule, as these penetrate the Arctic, following a wide variety of paths, they occlude rapidly. In summer the warm air masses are not modified appreciably, and, in this period, active fronts are observed in the Central Arctic. Interesting data have been assembled on the penetration into the Central Arctic of warm air masses from the Atlantic and Pacific oceans. These masses often disperse above the 100–200 m. cold earth layer throughout the troposphere to a height of 7–8 km., along the edge of the deep anticyclone which is centred over Alaska, and which gradually displaces itself eastward. Such a synoptic situation gives rise to outbreaks of cold arctic air from the polar regions over the European U.S.S.R. and western Siberia.

New data have shown that Sverdrup's theory of a layer of cold air lying over the ice needs further examination. The lower boundary of the layer of inversion is marked by turbulence which causes a vertical distribution of temperatures characteristic of unstable air masses. The so-called "cold layer" would be better named the "unstable layer". Until recently, changes in the altitude of the lower level of the stratosphere remained an open question. Regular radiosonde ascents have shown that the height of the tropopause over the Central Arctic Basin, including the region near the pole, is subject to the

[1]Presumably T2.

[2]This view has also been reached by North American scientists.

same fluctuations as over the mainland. The hypothesis of a continuously low stratosphere has been refuted. Similarly, new data have altered the notion of the vertical stratification of the atmosphere over the Central Arctic. Measurements of direct, diffused, and reflected radiation, of air temperature, of wind speed, and of ice and snow temperatures at various horizons, have yielded data for the study of the exchange of heat between the sea and the atmosphere. Contrary to previous ideas, the drift of 1950–1 showed that the annual radiation balance was positive, rather than negative. Such findings have great importance for the study of the global circulation of the atmosphere.

Terrestrial magnetism

Important data have been collected on the magnetic anomaly in the polar region. Investigations carried out, for the first time, between the magnetic north pole in the Canadian Archipelago, and the location of the previously imagined second magnetic pole, and to the northeast of the Novosibirskiye Ostrova, have shown that the second magnetic pole does not exist. Instead, the region of the supposed second magnetic pole was found in 1948 to be the centre of an enormous magnetic anomaly which extends across the entire Arctic Ocean. The meridians cluster near the Poluostrov Taymyr, and, to the northeast, form a thin bundle which stretches across to the magnetic north pole. Near the anomaly the horizontal component is greatly reduced, and measures 1,500 gammas instead of zero, while the inclination, or dip, is about 88.5 degrees, instead of 90 degrees. A close connection has been established between this magnetic anomaly and the Siberian maximum of the vertical component of the geomagnetic pole, which lies at the upper reaches of the Anabar and Kotuy rivers. Local magnetic anomalies have also been observed at various points in the Central Arctic. Sufficient data have been gathered to rule out the existence elsewhere in the Arctic of a second magnetic pole.

Observations have shown that diurnal magnetic disturbances at high latitudes in the Arctic have three maximums: morning, noon, and night. It appears that the lines of simultaneous morning maximums form a system of spirals radiating from the northwest end of Greenland, the pole of homogeneous magnetization of the earth. The Russians have drawn attention to the familiar fact that, if a stream of electrons is directed against a magnetized iron ball, these distribute themselves over the surface of the ball in spirals which emanate from its magnetic pole. Such a distribution is disclosed by luminosity. It is known that the distance between the pole of the magnetized ball and the point toward which the electrons fall depends on the energy (velocity) of the latter, and that the direction in which the spirals develop is determined by the sign of the charge born by the particles. The Russians suggest that streams of electrically-charged particles, emitted by the sun, and possessing differing velocities, penetrate the upper atmosphere of the globe, and reach different latitudes in accordance with their speed and mass. This may explain the peculiar geographical distribution of magnetic disturbances in high latitudes. Until recently, one zone of greater magnetic disturbance has been accepted in

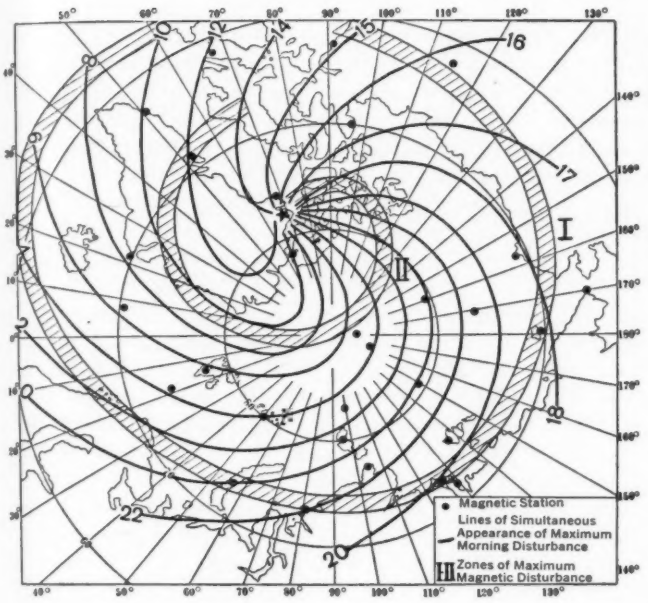


Fig. 15. Chart showing simultaneous appearance of maximum morning magnetic disturbances. The figures on the isochrons give hours in world time, from *Izvest. Akad. Nauk S.S.S.R., Ser. Geogr.* No. 5, 1954, p. 15.

the geomagnetic latitudes between 66 and 68 degrees, the region of maximum auroral activity. Sufficient data have now been collected to support the conclusion that there exists a second zone of intense magnetic disturbance, which is spiral in form, between the geomagnetic meridians of 80 and 85 degrees.[1] This hypothesis is based on the peculiarities of the midday magnetic storms in the region of the pole, and is supported by the predominance of zenithal forms of aurora and the distribution of the isolines of anomalous absorption in the ionosphere over Greenland and arctic Canada. The Russians claim that they have amassed data of great importance not only for the study of magnetic storms but also for the study of physical phenomena originating in the sun. To expand the work in this field still further, it has been announced that the Geophysical Institute of the Academy of Sciences is producing a series of precision instruments.

The 1954 expedition is on a scale surpassing that of any of the five previous Soviet efforts to explore the Central Arctic Basin. The expedition of 1941 has since been hailed as pioneering a new method—that of the successive landing of parties of scientists at a number of widely scattered points on the pack for short-term observations. Through this method, by the end of 1953, postwar expeditions had covered nearly two million square miles of the Arctic Basin. In 1954 the availability of large helicopters has made it possible to use this same method in conjunction with long-term observations at major drift stations.

[1]Recent Canadian work supports this view, but suggests that the spiral pattern is more complicated than appears in Fig. 15.

The result is that data can be collected more rapidly over a very large area (e.g., bottom profiles at least 200 km. in width can be constructed in the course of a twelve-month drift). This work has so far been concentrated mainly to the east of the Lomonosov Range, and it would appear that the implications of this range remain the principal object of study. The scale on which this study has been, and is being, pursued indicates that the problem which has been encountered here is very large and complex. If the Soviet government ever makes available the results of all this work, it will probably be clear that Soviet scientists have made an important contribution to the study of the Arctic Ocean, particularly of that part which lies between 150°E. and 70°W.

The press states that all stations were set up within twenty-three days of the departure of the main body from Moscow. It is clear that several hundred tons of freight have had to be delivered. In 1937 it took two months to establish the much smaller Papanin expedition. The apparent despatch with which the 1954 expedition was mounted indicates the experience which has been amassed by the Soviet Union in the establishment of major stations on the pack, in large scale supply and re-supply by air, and in the landing of heavy aircraft on unprepared sea ice. It is claimed that flights have been made throughout the polar night, that all landings have been made without accident, and that in no case was a landing effected more than a mile or two from the desired destination. Finally, it is claimed that no parties have experienced difficulties from the sudden development of cracks in the floes they have been occupying. But it is clearly felt that they are adequately equipped for the rapid emergency evacuation of men and equipment, should this prove necessary.

The Minister of the Sea and River Fleets recently announced that, by 1953, the annual turnover of freight along the Northern Sea Route had increased to four times that of 1940. This would indicate a figure of about 2,000,000 tons. It is likely that this increase has been achieved mainly by postwar capital development of the route. While it remains difficult to foresee a vastly greater increase in this figure in the immediate future, Soviet persistence in the effort to solve the mysteries of ice conditions in the Central Arctic clearly indicates that the route and the region are expected to acquire still greater importance for the Soviet Union.

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SURVIVAL PROBLEMS OF THE WATER-PIPIT IN BAFFIN ISLAND

George Miksch Sutton* and David F. Parmelee†

In rougher parts of southern Baffin Island the Water-Pipit (*Anthus spinoletta*) breeds regularly in considerable numbers. In 1877–8 Kumlien (1879, p. 74) found it "generally distributed on both sides of Cumberland Sound and the west shores of Davis Straits to lat. 68°N. at least, but nowhere very abundant." Soper (1928, p. 115) reported it as "common everywhere about Cumberland Sound" (summer of 1924); "very scarce" in the region of Isoa "during June and most of July" but "much more common toward the last of July" (1925); and "quite common" at Cape Dorset from June 1 on in the summer of 1926. Taverner (1935, p. 128) called it "common" in southern Baffin Island. Dalgety (1936, p. 582) found it the commonest bird near Ravenscraig Harbour, in Eglinton Fiord, from 14 to 29 August 1934. Shortt and Peters (1942, p. 347) considered it "The most abundant land bird of the high rocky coastal region about Hudson Strait", and reported it from Arctic Bay, Pond Inlet, and Pangnirtung. Bray (1943, pp. 532–3) observed it north to Fury and Hecla Strait, and evidently believed that it bred even farther north, in the part of Baffin Island known as Cockburn Land. Bent (1950, p. 35) included Arctic Bay and Pond Inlet in the breeding range, presumably on the authority of Shortt and Peters (1942). Wynne-Edwards (1952, p. 379) found it the third commonest bird at the head of Clyde Inlet in the summer of 1950—only the Lapland Longspur (*Calcarius lapponicus*) and the Snow Bunting (*Plectrophenax nivalis*) being more abundant.

Some of these authors, notably Soper, Dalgety, and Wynne-Edwards, discuss the pipit's seasonal fluctuations, and point out that in certain areas throughout which it does not breed it is sometimes common as a transient; none of them discusses fluctuations from year to year, however, and none expresses an opinion as to whether it is becoming more common or extending its range. Kumlien (1879, p. 73) is the only one who reports destruction of adults on a grand scale. He writes: "During the first of June we had the severest snow-storm of the season, and I think most of them perished. They would come around the observatory and shelter themselves as best they could. They were so far reduced that they were easily caught with the hand." Wynne-Edwards (1952, p. 379) reports the loss of a nest with six eggs (possibly robbed by a weasel or fox) and of one egg from another clutch of six. Pickwell (1947, pp. 7–12), discussing a nest with six young found by him on July 17 at 6,500 feet elevation near Frozen Lake, on the northeast side of Mount

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Rainier in the State of Washington, reports, but makes no attempt to explain, the death of two of the brood and the disappearance of two others within the following 12 days.

In the vicinity of the Royal Canadian Air Force station near the head of Frobisher Bay, Baffin Island, the Water-Pipit was the third commonest bird from 14 June to 22 August 1953. The Snow Bunting and Lapland Longspur were more common, the Horned Lark (*Eremophila alpestris*) almost as common. In a broad sense these four species occupied the same areas, but their numbers varied according to habitat, the bunting preferring rocks, the longspur grassy tundra, the lark gravel flats, and the pipit moss-grown slopes with southern exposure.

The pipit was less common at the airfield than on the rocky slopes just to the east and north, but we found one nest in the wide expanse of flat land near the airfield, and another in flat land just west of the mouth of the Jordan River. This was a surprise, for several authors had called attention to the species' avoidance of flat country in the nesting season (Sutton, 1932, p. 225; Soper, 1946, p. 420; and Wynne-Edwards, 1952, p. 379).

The pipit was the only species of the above-mentioned four to suffer really heavy losses of any sort during the summer of 1953. We found one adult dead near a road leading from the airfield to the bay shore (July 29); eleven nestlings (two nests) were destroyed by predators, and twenty-one well-developed young birds were found dead in nests (*see* Table 1). The latter had obviously not been bitten, chewed, or mauled; nor had they, as far as we could tell, been killed by nest parasites or disease. They must have died of starvation or exposure, or both, and the starvation almost certainly resulted from the inability of the parent birds to find sufficient insect food. Bad weather in July so immobilized the insects or cut down their rate of development that they were exceedingly hard to find. We, who were observing all this, considered ourselves fortunate in being able, day after day, to cross miles of tundra afoot without being bothered by mosquitoes. But the very factors which kept the mosquitoes down created a serious insect shortage for the birds, especially the pipit. We emphasize this because virtually all the young birds we found dead in nests were pipits.

The pipit's favourite slopes were comparatively free of wind in rough weather, and warm when the sun was out. On windy, bright days butterflies, crane-flies, and spiders were apt to be commoner here than elsewhere. The pipit's nest was likely to be found under the shaggy protection of the arctic heather, *Cassiope tetragona*, tucked away at the head of a little ravine or beside a big rock.

By foot we covered fairly often and regularly an 18-square-mile area north and east of the airfield. In the monotonous, plateau-like interior we did not encounter the pipit very often; but along the larger streams, and where the rocky land sloped abruptly down to salt water, the species was sure to be found. Several pairs nested along the nearer bank of the Sylvia Grinnell River, just west of the airfield. On the cliff-like western side of Hill Island, across the bay southwest of the airfield, several pairs nested. Near the mouth

Fig. 1. Typical Water-Pipit nesting habitat just north of Tarr Inlet, near the head of Frobisher Bay, 28 July 1953.

of the Jordan River, sixteen miles away, we saw many pipits on July 13 and from July 17 to 20. In the vicinity of a large lake at 68°31N., 71°22W., about fifty miles east-northeast of Wordie Bay, we saw a few pipits, both adult and young, on August 8. Our seeing the species at all the above-named places made the more noticeable our failure to find it at 65°20N., 77°10W., near Cape Dorchester, on August 11, and along the southeastern shore of Amadjuak Lake at 64°38N., 70°28W., on August 8 and 15. These two areas are largely flat. Soper (1946, p. 420) thus describes this part of Baffin Island: "From the swampy tundras of the west, relieved by no outcropping granites, the birds are entirely absent, except for a few scattered individuals that resort to beach lines during migration."

Behaviour

When we started our work at the airfield on June 15, we saw and heard pipits wherever we went. Most individuals that we looked at closely were a beautiful pinkish buff below, ashy gray above, and not very heavily streaked on the chest and sides. Since several of these sparsely streaked birds were singing, we assumed that all such birds were males and that the heavily streaked birds were females. In this we were quite wrong, as sexing of collected specimens showed. We saw no flocks: the birds were paired. We failed to find a nest or to see a bird carrying nest material.

On June 17 there was much flight-singing along the sheltered slopes north and east of the airfield, but most of the flight-songs seemed to be brief, perhaps because of the wind. On June 21 (minimum temperature 30.9°F, maximum 44.8°F, prevailing wind NNW., 16 m.p.h.) we observed several pipits singing flight-songs. The songs were a simple repetition of a *chwee* or *churee* note, but toward the middle of the series a slight change in *tempo* or enunciation gave the performance two distinct parts. As the notes continued, the singer continued to climb, usually rather gradually, sometimes steeply, then down he came with tail closed and lifted and wings partly spread to lessen the rapidity of descent. Singing sometimes started before the bird left the ground and continued after he had alighted (Murie *in* Bent, 1950, p. 33; Pickwell, 1947, p. 6), but such prolongation of the performance was exceptional.

On June 22 we found our first pipit nest (for details *see* pp. 87–8) while scouring the area in hope of finding the nest of a Harlequin Duck (*Histrionicus histrionicus*), a species we failed to record, though it had been reported from Baffin Island (Soper, 1928, p. 88; 1946, pp. 21–2). The pipit flew out with an explosive flutter of wings, hovered above the water a few feet away, and called *tsi-tsi* excitedly. When it alighted it did not feign injury. Its mate did not appear.

On June 24, in high country about a mile northeast of the airfield, we followed a pair of pipits about for some time, wondering if they had a nest. They were obviously much disturbed by our presence. Finally we collected the duller, more heavily streaked bird (GMS 11723), and found that it had a well-defined brood-patch. This bird's call-note had been *tsi-tsi*. The other bird, whose underparts were of a strongly pinkish shade, returned several times to the spot at which it had last seen its mate, calling *weet* sharply and performing brief flight-songs. We collected this bird (GMS 11722), and found that it had no brood-patch. The much-streaked bird proved to be a female, the other a male. In both specimens the gonads were much enlarged.

At 6 a.m. on June 25, after a full hour of observation, we found Nest 2. We first saw a pair of pipits quietly feeding along the lower edge of a big snowbank, and guessed that they were not far from their nest. The birds started walking down the slope together, the brighter in the lead. Presently this bird, which we believe to have been the male, flew northward about a hundred yards, alighting in plain sight. The female now gave several sharp *tsi-tsi* alarm notes. The male answered with a loud, far-carrying *weet*, not unlike one of the familiar alarm cries of the Wheatear (*Oenanthe oenanthe*). The female was obviously ill at ease, and finally approached the male with fluttering wings and loud cries which resembled those of a begging nestling. We had been watching the male, so knew that he had been looking for food; but we supposed he had been eating all he had found. It now became apparent that he had gathered a considerable mouthful, for he fed the female, even picking up and giving to her bits which fell to the ground. Between about 4 a.m. and 5.55 a.m. she flew to her mate for food fourteen times. After her fourteenth trip, her behaviour changed. She stood high for an instant just after alighting, looked about, then lowered her head and walked directly to

the nest. Her every activity had been, most of this time, within a few yards of the nest except when she flew to the male to be fed. Before each feeding her *tsi-tsi* cries accelerated until they ran together in a continuous sound of begging. When the female flushed she fluttered downslope, touching the ground occasionally as she flew.

On June 30 we came upon a brood of young only a few days out of the nest. We found the young birds while moving cautiously along the edge of a small rock-rimmed lake stalking a male Old-squaw (*Clangula hyemalis*). The several fledglings sprang up all at once and, though noticeably stub-tailed, flew fairly well. This brood was probably at least 15 days old. Hatching having taken place not later than June 15, and the incubation period having been at least 12 days (Pickwell, 1947, p. 12), the last egg of the clutch must have been laid about June 3—a very much earlier date than that on which we found our first nest. On consulting the meteorologists at the airfield, we learned that there had been an unusually mild spell in late May and early June, a period spring-like enough, obviously, to have led some pairs of pipits to proceed with nesting. This was the only brood which we know to have been reared wholly during June, but our several observations of nest-failure in mid-July led us to wonder whether the 1953 crop of young pipits might have been largely of June broods. In this connection it is interesting that Wheeler (*in* Austin, 1932, p. 175) saw "young able to fly short distances" on June 16 in the Kiglapait Mountains, in Labrador; that Wynne-Edwards (1952, p. 379) found a nest with six eggs at the head of Clyde Inlet on June 13; and that there are, in the Colorado Museum of Natural History, eggs collected along the Chipp River, on the Arctic Slope of Alaska, as early as May 27 (Bailey, 1948, p. 286).

In all, we found fourteen nests between June 22 and July 18. Observations at these nests and information gained through collecting specimens, convinced us that the male pipit does not incubate. Austin (1932, p. 175) states that "incubation is performed by both sexes", but none of the three adult males we collected (respectively on June 24, 26, and 29) had the slightest indication of a brood-patch; the one adult female we collected had a well-defined brood-patch; and each of the four incubating birds we caught at the nest and banded had a well defined brood-patch but no indication of a coiled vas deferens in the region of the anus. Furthermore, repeated observation convinced us that birds which approached their mates with fluttering wings and begging cries were females; that birds which gave a double alarm note (*tsi-tsi* or *chi-chi*) near the nest were females; and that birds which gave a *weet* alarm note at the nest were males. We never observed an incubating female receiving food from her mate at the nest proper. We found Nest 7 (*see below*) by watching a male, with mouth full of food, alight near the nest; the female left the nest, approached her mate with fluttering wings, and received the food.

Our latest date for a full flight-song was July 13, near the mouth of the Jordan River. V. C. Wynne-Edwards told us of hearing a brief song some miles east of the airfield on July 23. On August 1 we noted several adults in moulting condition, one of them stub-tailed.

Incubation period

The incubation period at one nest (Nest 2), which we visited frequently, was shown to be at least 11 days, 23 hours, and 15 minutes (6 a.m. on June 25 to 5.15 a.m. on July 7), and almost certainly longer, since when we found the nest the clutch was complete. Pickwell (1947, p. 12) found the incubation period to be "a full twelve days". According to 'The handbook of British birds' (1948, Vol. 1, p. 205), the incubation period of *Anthus s. spinoletta* of the Old World is "about 14 days".

At one nest (Nest 7), four eggs hatched within a 24-hour period. At another nest (Nest 8), a five-egg clutch hatched within at least 16 hours, at most 25 hours and 30 minutes. Size-variation in the brood of six found in Nest 10 clearly indicated that hatching had not been simultaneous and that incubation had begun well before the clutch was complete.

Fledging period

The fledging period in Baffin Island was at least 12 days, at most 14 days (Nest 3). Johnson (1933, pp. 114–5) reports a fledging period of at least 13 days. Wynne-Edwards (1952, p. 379) calls attention to the possibility that young pipits normally leave the nest before they can fly.

Nest observations

All of the fourteen nests found were lined solely with grass; in none was there a feather, tuft of bog-cotton, or plant-down of any sort. Moss was included in the foundation material, but in general the walls and bottoms were of grass. All the nests were more or less hidden under vegetation, principally *Cassiope tetragona*, but none was in a crevice among rocks in the sort of site preferred by the Snow Bunting. Soper (1946, p. 420) describes a pipit nest having such a site.

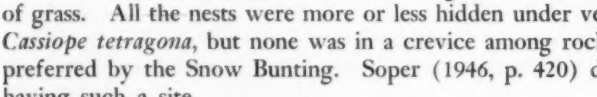

Fig. 2. Nest and eggs of Water-Pipit, near the head of Frobisher Bay, 4 July 1953.

Clutch-size varied. Two nests held three eggs each, but we were not sure that either of these clutches was complete. Three nests held six eggs each. Nine nests held five eggs each. Of the seventy-nine eggs known by us to have been laid, at least five did not hatch. Of the fifty-seven young which we know or believe did hatch, only three were known by us to have fledged successfully; twelve may possibly have fledged, for the nests held particles of feather-sheaths; ten may or may not have fledged (we saw them only once); eleven were destroyed, while still in the nest by predators; and twenty-one died in the nest from starvation or exposure (or both) when almost fledged.

The following notes give brief details on nesting sites and observations at the nest. Our data on hatching success of the fourteen nests is summarized in Table 1.

Nest 1. Found June 22 in *Cassiope* on a bank overhanging a swift stream near the Hudson's Bay Company's post: 6 eggs. June 25, 6 eggs; July 22, one egg and feather-sheath particles, so the brood may have fledged.

Nest 2. Found June 25 on a high, southward-facing sheltered slope, half a mile northeast of the airfield: 5 eggs. June 27, 5 eggs; July 6, about 7.30 p.m., 3 young, one of which was not yet dry, and 2 eggs; July 7, 5.15 a.m., 3 young and 2 eggs; July 8, about 6 a.m., female banded, 5 young. On July 23 nest was empty, but contained feather-sheath particles, so the brood may have fledged.

Nest 3. Found June 28, well sheltered by *Cassiope*, high on a slope with a southern exposure: 5 eggs. July 2 to 5, nest visited daily, and female banded on July 5. July 10, 6 a.m., 4 young and one egg; July 16, 4 young and one egg; July 22, one well-developed dead nestling and one egg in the nest, 3 alert-looking nestlings huddled nearby. Nestlings banded; although at least 12 days old they could not fly, but we saw them flying two days later.

Nest 4. Found June 30 among *Cassiope* on a steep slope along the west side of the Sylvia Grinnell River, about half a mile from its mouth: 3 eggs. July 1, 3 eggs; July 15, 3 young; July 25, 3 young all dead and somewhat decomposed. The young probably died about July 18 or 19.

Nest 5. Found July 1 among blooming *Cassiope* on a steep slope along the west side of the Sylvia Grinnell River in a sheltered spot with southern exposure: 3 eggs. July 2, 2 eggs only; July 15, nest empty, no feather-sheath particles.

Nest 6. Found July 1 in moss on an almost perpendicular two-foot bank in a sheltered spot along the southwest edge of a rocky outcrop on Davidson Point: 6 eggs. July 2, 6 eggs; July 12, 6 young; July 17, nest found scattered, probably the work of a dog.

Nest 7. Found July 4 at the base of a mossy hummock about thirty yards east of the building in which we lived: 5 eggs. July 5 to 12, nest visited daily; incubating bird banded on July 5. July 11, 7 a.m., 4 young and one egg; July 16, 4 young and one egg; July 21, 4 well-developed dead nestlings and one egg, parent birds had left the vicinity.

Nest 8. Found July 5 in a sheltered mossy spot among large rocks: 5 eggs. July 6, incubating bird banded. July 7 to 16, nest visited daily. July 8, about noon, 5 eggs; July 9, 2.30 p.m., 3 small young and 2 eggs, one of the parents was seen to carry an egg-shell from the nest; July 10, 6.30 a.m., 4 young and one egg, at 4 p.m., 5 young; July 16, 5 sturdy young; July 21, 3 well-feathered young dead in nest and the parents had left. Two young may possibly have fledged.

Nest 9. Found July 6 among *Cassiope* on a high mossy slope with southern exposure about a mile and a half northeast of the airfield: 5 eggs. Nest not visited again.

Nest 10. Found July 7 among moss and *Cassiope* on a vertical bank about four feet above a narrow area of wet grassy tundra, half a mile east of the airfield: 5 eggs. July 22, 4 well-developed dead nestlings and one egg. The young must have died some days previously.

Nest 11. Found July 10 in a thick growth of *Cassiope*, twenty feet below the top of a steep, moss-covered rocky slope, about two miles east of the airfield: 5 small young. Nest not visited again.

Nest 12. Found July 12 in flat grassy tundra about a quarter of a mile north of the airfield: 6 young, the smallest of which had hatched very recently. Young were of various sizes. July 15, 6 young; July 17, 6 young; July 21, 6 young all dead and somewhat decomposed in the nest.

Nest 13. Found in mid-July by a civilian employee at the airfield on a mossy hummock in marshy tundra near a rocky slope on Davidson Point: 5 eggs. July 30, nest found torn from its site; some feathers of fairly well developed young birds were among the remains.

Nest 14. Found July 18 among *Cassiope* in the middle of a wide expanse of grassy tundra, well away from rocks, not far from the mouth of the Jordan River: 5 fairly well developed young. Nest not visited again.

Table 1. Fourteen Baffin Island Water-Pipit nests

Nest	*Contents when found*	*Young known to have hatched*	*Eggs known not to have hatched*	*Young found dead in nest*	*Young known to have fledged*	*Young possibly fledged*
1	6 eggs	5	1	0		5
2	5 eggs	5	0	0		5
3	5 eggs	4	1	1	3	
4	3 eggs	3	0	3		
5[1]	3 eggs		1			
6[2]	6 eggs	6	0			
7	5 eggs	4	1	4		
8	5 eggs	5	0	3		2
9[3]	5 eggs					
10	5 eggs	4	1	4		
11[3]	5 young	5	0			
12	6 young	6	0	6		
13[3]	5 eggs	5	0			
14[3]	5 young	5	0			

[1] This nest held two eggs (only) on July 2. We did not visit it again before July 15, on which date it was empty. Absence of feather-sheath particles indicated that no young fledged.
[2] Destroyed by predator.
[3] We did not visit this nest a second time.

Nest success and species survival

Table 1 reveals an astonishing fact: not one nest of the fourteen did we know to have been 100 per cent successful in fledging, and only one (Nest 3) did we know to have been successful at all. In this nest five eggs were laid. Of the four young which hatched, three left the nest shortly before being able to fly, while one died about the time its siblings left the nest. Seven of the fourteen nests we know to have been 100 per cent unsuccessful. Of these at least two were destroyed by predators and five failed, probably because of bad weather.

On the basis of our observations, the pipit was the least successful in its nesting of all the birds of the Frobisher Bay area in the summer of 1953. As Table 1 shows, the principal losses were of well-developed nestlings, and this loss took place chiefly during the third week of July, when the weather was especially bad. We were away from the airfield, at the mouth of the Jordan River, from July 17 to 20. The weather during most of that period was foul. When we returned, on July 21, we found three nestfuls of young pipits which

had died while we were away. On July 22 and July 25 we found more nestfuls of young so badly decomposed we could not save them as skins, so the broods must have died some days before. The most lethal period probably was the wet, foggy, cold, and windy 48-hour period of July 18–19. The weather data for this period are given in Table 2.

Table 2. Weather conditions at Frobisher airfield, 17 – 21 July 1953

Date	*Minimum air temp. °F*	*Maximum air temp. °F*	*Minimum wind*	*Maximum wind*	*Prevailing wind*
July 17	37.4	53.1	Calm	16 m.p.h. (NW.)	10 m.p.h. (NW.)
July 18	36.2	41.6	Calm	30 m.p.h. (SE.)	13 m.p.h. (S.–SE.)
July 19	36.0	40.8	9 m.p.h. (S.–SE.)	21 m.p.h. (S.–SE.)	15 m.p.h. (S.–SE.)
July 20	35.1	45.1	Calm	30 m.p.h. (S.–SE.)	17 m.p.h. (S.–SE.)
July 21	35.9	46.4	4 m.p.h. (W.–NW.)	40 m.p.h. (NW.)	17 m.p.h. (NW.)

This breeding record for fourteen pairs of pipits is appallingly poor, and the ultimate fate of any pipit population obliged to live under continuing conditions so unfavourable to reproduction is obvious. For a time in late July we thought that the whole pipit crop of our area had failed. However, from mid-July on we saw many young birds. On July 18, not far from the mouth of the Jordan River, we caught a strong-flying young bird with tail about one inch long. We let this bird go. On July 27, along the west side of Tarr Inlet, we happened upon a brood not long out of the nest. On July 24 we saw a few scattered young birds in high country northeast of the airfield. A female (GMS 11789) collected that day had fully developed flight feathers and might well have been of an early June brood. From July 25 to August 10 we saw several young birds daily near the airfield. On August 1 we collected a juvenal male (GMS 11799) with flight feathers still slightly sheathed at the base. On August 10 we saw a stub-tailed bird not long out of the nest.

These late records for young birds, far from being proof of two broods, are nevertheless evidence that some eggs or nestlings survived the lethal mid-July weather. A question naturally arises concerning the nests found by us: were they the most findable, hence the most exposed and vulnerable to the weather? Does Table 1 present a distorted and misleading picture? We believe not. We believe that throughout the whole Frobisher Bay area nestlings which were well developed in mid-July perished between July 18–19. We further believe—and suggest that careful observations along this line be made—that the only young birds which died were almost ready to fledge, i.e., in need of much food; that younger birds, not in need of so much food, survived; and that pairs which lost well-developed nestlings made no attempt to nest again. Granting that a pair, having lost a brood on or about July 19, might attempt to re-nest, let us review the requirements: at least a day would be needed for nest-building, 3 or 4 days for egg-laying, 12 days for incubation, and 13–14 days for fledging (Johnson, 1933, pp. 114–5): a total of 30–31 days. Stub-tailed young which we saw on August 10 were obviously not from a brood reared after July 19. We saw no stub-tailed young later than August 10.

The fact that we examined so many dead nestlings continues to amaze us. Why were these not eaten by predators? Although we did not see a trace of a weasel (*Mustela erminea*) or fox (*Alopex lagopus*) near any of the pipit nests we were observing, lemmings (*Lemmus trimucronatus* and *Dicrostonyx groenlandicus*) were common. Yet not one of the dead pipit nestlings had been chewed at in the slightest.

Description of specimens

The following four adult Water-Pipits were collected near the airfield. They represent the well-known race *Anthus spinoletta rubescens*. We have not, however, had specimens of the races *A. s. pacificus* and *A. s. monticola* for comparison. Measurements are in millimetres.

GMS No.	*Sex*	*Date*	*Wing*	*Tail*	*Culmen*	*Tarsus*
11722	Male	June 24	84.0	65.0	13.0	23.5
11723	Female	June 24	82.5	66.0	12.5	22.5
11728	Male	June 26	85.0	64.0	13.0	24.0
11733	Male	June 29	84.0	65.0	13.5	23.0

Two of these specimens (female, 11723; male, 11733) are heavily streaked on the chest and sides, the other two are not. The heavily streaked male is unique in this series in having a complete, though narrow and not very noticeable, dark malar stripe. The heavily streaked female has a much interrupted malar stripe. The comparatively unstreaked specimens (11722, 11728) differ from the other two in being more vinaceous below (especially 11722) and in having a much reduced and interrupted malar stripe. The four specimens vary as regards the white in the tail. The outermost rectrices have about the same amount of white throughout the series, but the next pair are whitest in 11728 (male) and 11723 (female).

The two specimens with heavily streaked plumage may be in their first breeding plumage (*see* Ridgway, 1904, p. 13, footnote), but Dr. Kenneth C. Parkes, who at our request examined the extraordinarily fine series of adult Water-Pipits in the Carnegie Museum collection in Pittsburgh, believes that degree of streaking may not be an age phenomenon, but rather "some sort of incompletely developed sexual dimorphism".

Dr. Parkes's comments are so interesting that we quote at length from his letter of 24 February 1954: "I segregated out all of our presumably breeding pipits, and found that our series segregated roughly into three groups. The first consisted of those birds which varied from almost immaculate to those with a partial (broken) ring of spots across the chest. A fairly well-defined middle group has a very clear-cut and definite ring of spots across the chest, but little additional spotting. The third group has the most spotting, varying from the single ring supplemented by additional spots to those few extreme birds with heavy streaking . . . Among the unstreaked birds there is little or no correlation between sex and amount of streaking . . . On the other hand, the heavily streaked end . . . is dominated by females."

Dr. Parkes adds that "there is no indication whatsoever of any geographic correlation; each category contains birds from points as far apart as Labrador

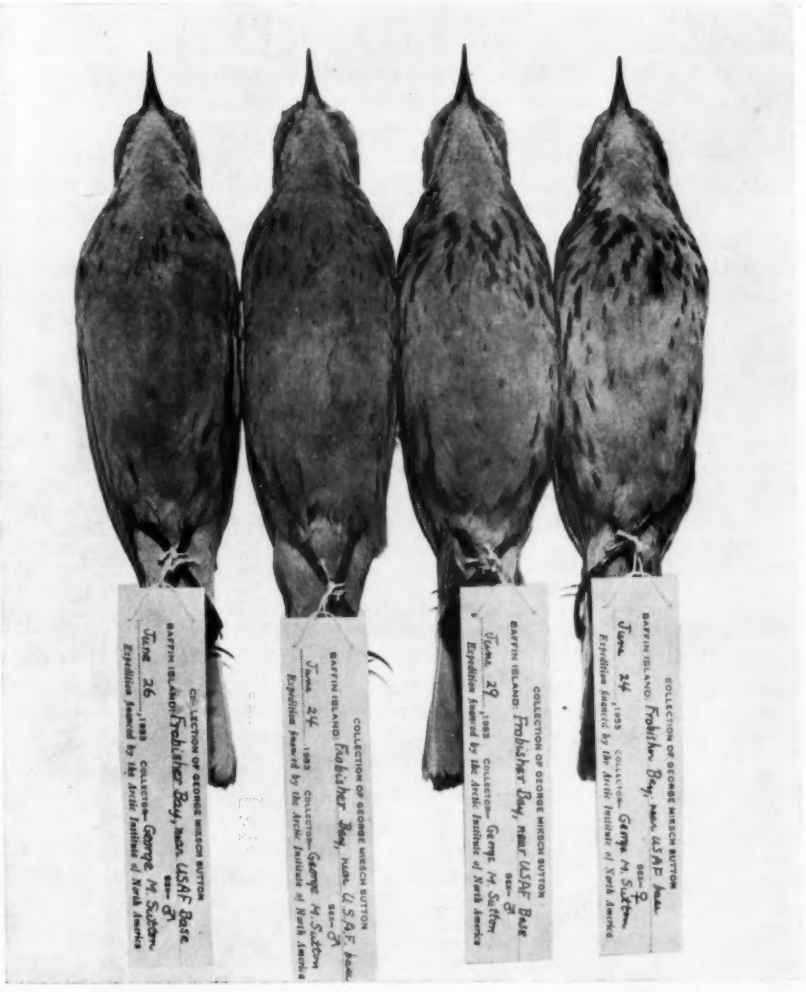

Fig. 3. Adult Water-Pipits in breeding plumage, collected near the head of Frobisher Bay in June 1953. The only female is at the right. This bird's mate is second from the left.

and the Mackenzie Delta". He further states that "on the average, the less heavily streaked birds have the best development of the bright pinkish-buff ground color".

Our two specimens in full juvenal plumage (male, GMS 11799; female, GMS 11789) are much alike, but the male is paler on the chin and throat, has a much more noticeable buffy white superciliary spot back of the eye, and has more white in the outer rectrices than the female.

We find no sexual dimorphism in the four nestlings. In all the chest-streaking is dark and heavy and the rich buff of the belly is slightly tinged with pink. The natal down, which clings in profusion to the sides of the crown, middle of the hind neck, scapulars, and rump, is mouse gray.

This work was made possible by a grant from the Arctic Institute of North America.[1] We also wish to thank Douglas Tesch, of the Meteorological Division of the Canadian Department of Transport, for concise weather data; V. C. Wynne-Edwards, of Aberdeen University, for help in the field; and Kenneth C. Parkes, of the Carnegie Museum in Pittsburgh, for his opinion on sequence of plumages and colour variation in *Anthus spinoletta*.

[1]With funds provided by the U.S. government.

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PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY OF THE SEAS TO THE WEST AND NORTH OF ALASKA

E. C. LaFond*

ALASKA, with the north Pacific Ocean to the south, a transition zone through the Bering and Chukchi seas to the west, and the Arctic Ocean to the north, is exceptionally well situated for studies in oceanography. These diverse water masses contain a variety of ecological environments, and different physical and geological conditions. However, owing to problems of transportation and lack of facilities, relatively little oceanographic work has been done in the seas around Alaska.

Most information on soundings, currents, and ice conditions in the area has come from commercial ships engaged in whaling and shipping. Even much of the information on physical oceanography and marine geology has been obtained incidental to other operations. The main studies of the physical and chemical structure of the water were made by U.S. Coast Guard vessels staffed with University of Washington oceanographers during the summers of 1933, 1934, 1937, and 1938. On these cruises serial stations, making oceanographic sections, were occupied throughout the eastern Bering Sea and Bering Strait, and along one line to Point Barrow. Another prewar cruise was made by the *Maud* which obtained considerable data between Herald Shoal and Ostrov Vrangelya (Wrangel Island) (Sverdrup, 1929).

During the war the principal oceanographic work carried out consisted of bathythermograph observations in the southern part of the Bering Sea. Postwar investigations consisted of scattered bathythermograph observations and oceanographic stations from icebreakers running through the Bering and Chukchi seas to Point Barrow in 1946, 1948, and 1950. These investigations were made by personnel of the U.S. Coast Guard, Scripps Institution of Oceanography, University of Washington, and U.S. Hydrographic Office. In 1947 a U.S. naval ship staffed with U.S. Navy Electronics Laboratory and Scripps observers occupied stations through the Bering and central Chukchi seas to a latitude of 72°N. In 1949 both Canadian and United States naval ships investigated the southern and eastern Bering Sea and the eastern Chukchi Sea to a latitude of 73°N.

Although the number of cruises in this area appears impressive, it must be remembered that all the data were taken in midsummer. During this season significant week-to-week changes take place in the physical properties of the water. Furthermore, additional duties or programs of the ships made it impossible to locate or time stations to the best advantage for adequate coverage.

*U.S. Navy Electronics Laboratory, San Diego, California.

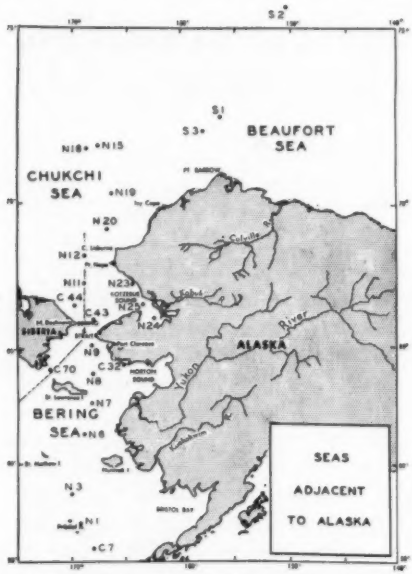

Fig. 1. Seas adjacent to Alaska showing location of oceanographic stations.

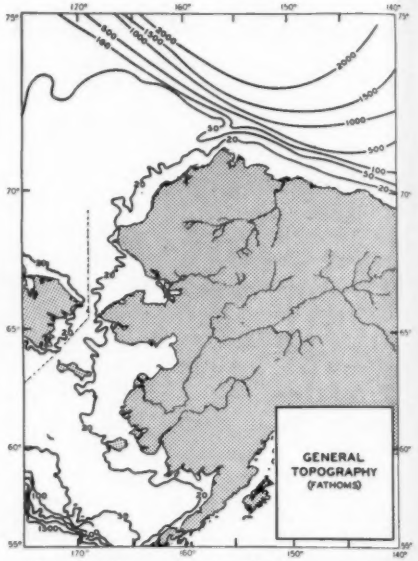

Fig. 2. General submarine topography around Alaska.

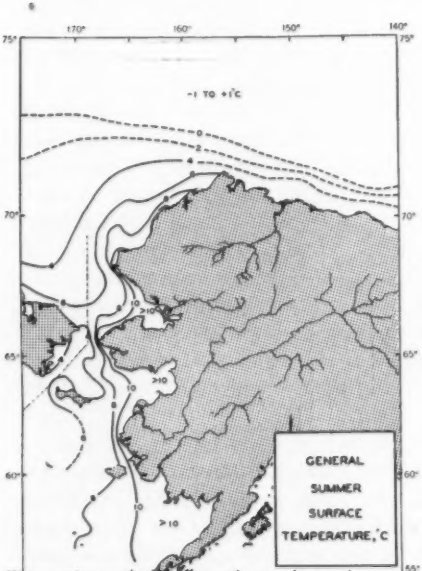

Fig. 3. General summer sea surface temperature around Alaska.

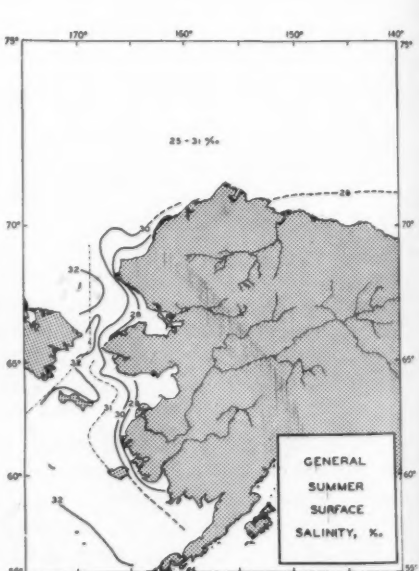

Fig. 4. General summer sea surface salinity around Alaska.

Submarine topography

The Bering Sea is bounded on the south by the Aleutian Island arc, and on the north by Siberia and Alaska (Figs. 1 and 2). In the southwest it is an abyssal ocean basin; the deepest part, around 2,100 fathoms (not shown on Fig. 2), has a rather flat floor. A steep slope connects this basin to the shallow continental shelf that extends throughout the northern and eastern Bering Sea, Bering Strait, and most of the Chukchi Sea. This shelf is remarkably level and smooth. It has an average slope of 3 to 4 inches a mile, and is believed to be flatter than any land feature of comparable area (Buffington *et al.*, 1950, p. 2).

The floors of the northern Chukchi and Beaufort seas fall off steeply into the Polar Basin, to depths of over 2,000 fathoms (Emery, 1949). Just north of Point Barrow a depression, the Barrow Sea Valley, crosses the continental slope to the northeast.

Sediments

Bottom sediments collected by various expeditions indicate that the floor of the Bering Sea is mainly sandy, with some large areas of mud or sandy mud west of 170°W., and sand and gravel on the edge of the continental shelf. The muddy area appears to stretch north into the Anadyrskiy Zaliv (Gulf of Anadyr) which receives the outflow of several large Siberian rivers. Gravel and rock were found in spot samples taken near the islands, particularly along the edge of the continental shelf south of the Pribilof Islands, and certain areas along exposed coastlines, such as near Seward Peninsula. Coarse sediments are also found in Bering Strait. In the Chukchi Sea nearshore areas are sandy with occasional gravel patches, and sediments, in general, become progressively finer in texture northwards to a zone of mud and sand. North of Alaska the bottom appears to be largely mud. In all areas occasional isolated patches of mud, sand, and gravel are found.

Sediments in this area are mainly derived from the large rivers entering the Bering and Chukchi seas from the Alaskan and Siberian coasts, which deposit large amounts of silt and clay, especially towards the north in the Chukchi Sea, and from ice rafting. Material carried by rivers flowing under ice freezes to the under surface, and ice freezing to the bottom and banks picks up sediment. In the spring break-up the ice may be carried out to sea and the accumulated sediment may be scattered anywhere in the area.

Horizontal temperature and salinity structure

The horizontal temperature distribution in the surface water to the west and north of Alaska is shown in Fig. 3. Relatively warm surface water is found in the southern and eastern part of the Bering Sea (Goodman *et al.*, 1942, pp. 125–6). Currents move this water across the slope and shelf of the Bering Sea in a northwesterly direction. In summer warmer waters are found near the Alaskan coast, the temperatures decreasing with distance from the coast (LaFond and Pritchard, 1952, p. 72). Thus isotherms, in general, tend to follow the coast bending into Norton Sound, Kotzebue Sound, and

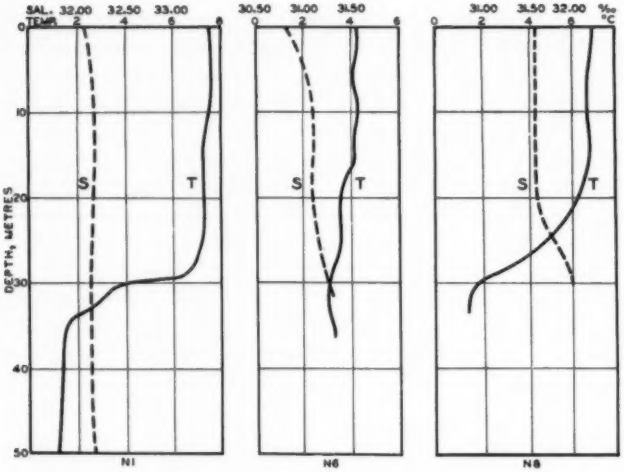

Fig. 5. Examples of vertical temperature and salinity in Bering Sea in summer (*see* Fig. 1 for location of stations).

around Cape Lisburne, with highest temperatures in the inner parts of Norton Sound and Kotzebue Sound. Colder water appears to come from the western side of the Bering Sea, especially just north of St. Lawrence Island. Colder water is also found in the Chukchi Sea; it apparently originates just north of, and along, the Siberian coast. North of 70°N. surface temperatures fall abruptly at the boundary of the ice pack. During the summer the temperatures sometimes drop to less than –1°C, and usually vary between +1° and –1°C within the scattered ice.

Changes in horizontal salinity distribution also occur in an east–west direction (Fig. 4). In general, less saline water is found along the Alaskan coast, particularly in the inner parts of Norton and Kotzebue sounds, and the isohalines in the southeastern Bering Sea tend to run southeast–northwest, then eastward past St. Lawrence Island, bending into Kotzebue Sound. In the northern Chukchi Sea and to the north of Alaska the surface salinity is difficult to forecast as it is largely determined by the southern limit of the ice pack. Readings ranging from 25 to 31 parts per thousand in summer have been obtained.

Vertical temperature and salinity structure

Examples of the vertical temperature structure from bathythermograms and the vertical salinity structure from oceanographic stations (Fig. 1) are illustrated in Figs. 5, 6, and 7. Near the Pribilof Islands (Fig. 5, N1), the typical summer temperature structure shows a sharp layering with no appreciable salinity gradients. Farther north, between St. Lawrence and Nunivak islands (Fig. 5, N6), both the salinity and temperature are nearly uniform with depth. North of St. Lawrence Island (Fig. 5, N8), sharp vertical gradients again appear. In Bering Strait the warmer, less saline water near the Alaskan coast, causes large gradients of temperature and salinity near the

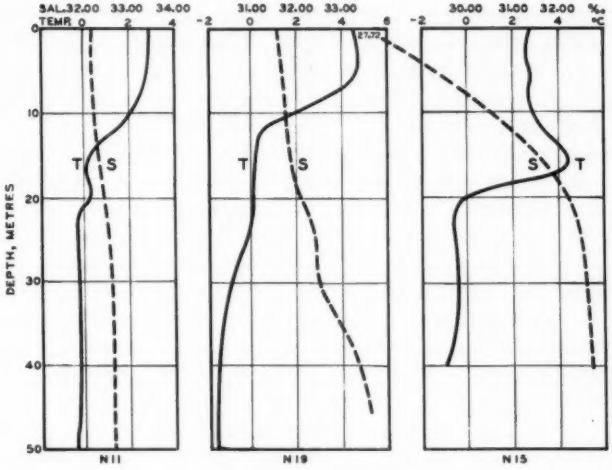

Fig. 6. Examples of vertical temperature and salinity in Chukchi Sea in summer (*see* Fig. 1 for location of stations).

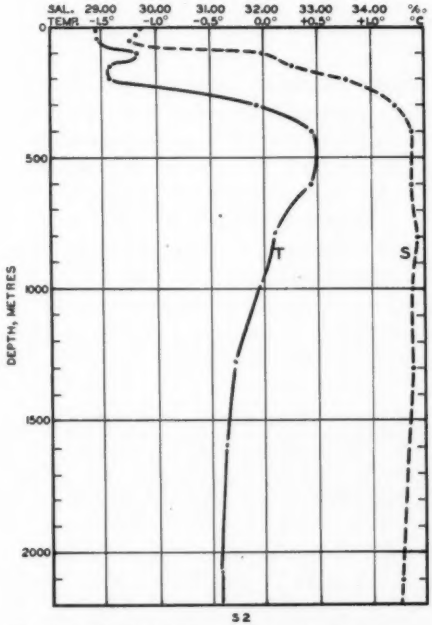

Fig. 7. Example of vertical temperature and salinity in Beaufort Sea in spring (*see* Fig. 1 for location of station).

surface on that side of the channel. In the Chukchi Sea the vertical temperature structure is more variable in summer. Just north of Bering Strait and off Cape Lisburne, shallow seasonal thermoclines and relatively weak salinity gradients are found. Near the boundary of the ice pack there is a pronounced maximum around 15 metres with very irregular temperature structures above and in the main thermocline, and the salinity is low due to meltwater. The

high temperature maximum below the surface is attributed to warm water of higher salinity brought into the area through Bering Strait, which sinks on meeting the cold, but low-salinity, meltwater from the ice pack.

The vertical distribution of temperature and salinity in the Beaufort Sea in spring is shown in Fig. 7 (Worthington, 1953, p. 545). The temperature is near freezing to a depth of 200 metres. Below this depth a subsurface maximum occurs around 500 metres. This relatively warm layer is believed to be drawn into the region from the Atlantic Ocean, though some modification must take place as the salinity is lower than that of the North Atlantic.

The temperature and salinity curves of the Bering and Chukchi seas are typical of summer observations (Figs. 5 and 6). Speculations on the temperature structure for other seasons based on previous observations in the southern Bering and northern Chukchi seas are shown schematically in Figs. 8 and 9 by superimposing a heavy temperature–depth curve for each season on a block of ocean.

North of the Aleutian Islands the temperature during winter is virtually the same from the surface to depths greater than 120 metres (Fig. 8) (Pattullo *et al.*, 1950). Slightly higher temperatures around 150 metres are attributed to subsurface advection and are believed to be characteristic of the region. By spring the temperature–depth curve begins to show steps indicating successive heating and mixing of the water. By summer these steps become large and merge into the seasonal thermocline. Frequent winds in this region cause the surface layer to remain at the same temperature even though heat is being added to the water. In the fall the isothermal layer becomes deeper as a result of increased mixing and cooling.

In the northern Chukchi Sea (Fig. 9) the surface is ice-covered in winter. The cooled surface water develops vertical convection currents which produce isothermal surface layers. By spring the ice becomes thicker and the water remains in isothermal layers. Minor gradients are the result of subsurface advection. In summer the surface layer is heated; in addition, warm water is brought into the region from the south at a subsurface level, creating a

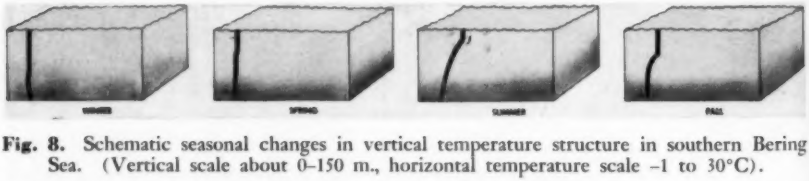

Fig. 8. Schematic seasonal changes in vertical temperature structure in southern Bering Sea. (Vertical scale about 0–150 m., horizontal temperature scale –1 to 30°C).

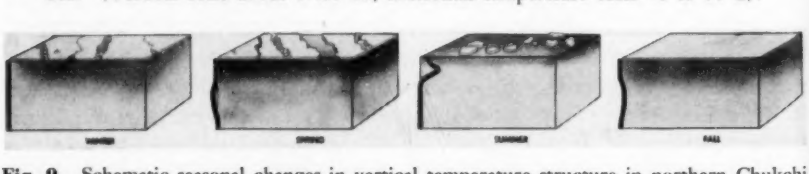

Fig. 9. Schematic seasonal changes in vertical temperature structure in northern Chukchi Sea. (Vertical scale about 0–150 m., horizontal temperature scale –1 to 30°C).

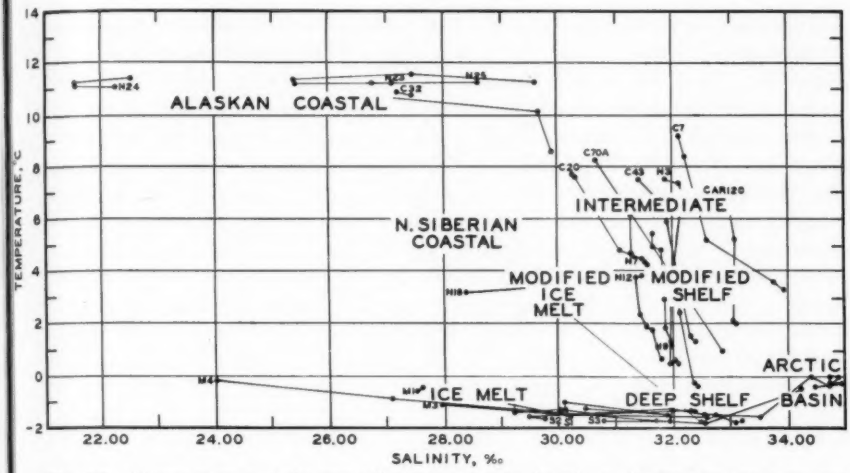

Fig. 10. Water masses of the seas adjacent to Alaska, based on observed temperature and salinity relation. Dots and fine connecting lines are observed T–S data.

subsurface temperature maximum. By fall the surface again freezes and the cooling and mixing processes create an isothermal layer over a slightly negative gradient.

Water masses

The study of temperature–salinity (T–S) relationship provides a convenient method for determining the characteristics, origin, and movements of water masses (Sverdrup *et al.*, 1942, pp. 739–45). The temperature and corresponding salinity at the surface and each subsurface observation level for various oceanographic stations in the seas to the west and north of Alaska (Fig. 1) are plotted in Fig. 10. The individual T–S values are shown by a dot and those for a complete (vertical series) station are connected by a fine line. The source of data are indicated: Nereus (N), Chelan (C), Maud (M), Skijump (S), and Carnegie (CAR). For these summer data a certain consistency in the T–S relationships of this shallow water Alaskan region was maintained. Because of this consistency it has been possible to establish eight water masses having a definite T–S value as shown in Fig. 10. The *Alaskan Coastal* water for example, is characterized by high temperatures (10–12°C) and low salinity (<30 o/oo). It is found along the western coast of Alaska as far north as Point Barrow and attributed largely to the river runoff of warm fresh water. The *Ice Melt* water is found in the region of arctic pack and has low salinity from the melting of relatively fresh (low salinity) sea ice, but the temperature still remains just above freezing. The *Deep Shelf* water in the Bering and Chukchi seas is probably the result of winter freezing at the surface creating low temperatures below the ice, combined with higher salinity. This water mass persists near the bottom in summer throughout most of the Bering

and Chukchi seas with the exception of the Bering Strait region. Deep *Arctic Basin* water is relatively cold but of still higher salinity. As mentioned previously this water must come from the Atlantic Ocean. Another source of water in the Chukchi Sea is believed to be from the west, along the Siberian coast. This *North Siberian Coastal* water has a relatively low salinity due to fresh water from the large rivers in this region. Its temperatures run lower than that of *Alaskan Coastal* water coming from the Bering Sea. Where two or more water masses mix the modified water masses are termed *Modified Shelf*, *Intermediate*, and *Modified Ice Melt* water. *Modified Shelf* is merely the summer-heated winter *Deep Shelf* water; *Intermediate* results from mixing of *Modified Shelf* and *Alaskan Coastal* water; and *Modified Ice Melt* appears to be largely a surface mixture of *Ice Melt* and *Intermediate* water. By means of these established water masses it is usually possible to determine the origin and direction of flow from the continuity in the measured T–S relation.

Currents

The general flow of surface water in the area around Alaska during the summer has been studied. There is a general northerly flow from southeastern Bering Sea through Bering Strait (Fig. 11) (Barnes and Thompson, 1938, p. 162). The flow of the Alaskan coastal water tends to follow the contours of the coast, deflecting into Norton Sound, closely hugging the Alaskan side of Bering Strait, deflecting into Kotzebue Sound, continuing north around major promontories, and finally flowing north from Point Barrow. In this region the current is believed to combine with water from the east in the Beaufort Sea. The two types of water merge and after flowing north, appear

Fig. 11. Schematic surface currents around Alaska in summer.

to create an anti-clockwise circulation in the northwest. Currents along the northwestern side of the Bering Sea are weaker and more variable; occasionally they have been known to flow to the south. However, the predominant drift is to the north and enters the strait on the western side. Another current flows into the southern Chukchi Sea from the north coast of Siberia (Ratmanov, 1937, p. 111), and, after bending around in Kotzebue Sound, turns back to the northwest. Local winds tend to affect the circulation and consequently the flow shown in Fig. 11 must be considered as schematic.

Ice

The ice conditions in the Bering and Chukchi seas are not only dependent on the season but also show year-to-year variations. For example, the southern limit of the arctic pack in the Chukchi Sea was 72°N. in the late summers of 1947 and 1948, while in 1950 it was 73°N. If the wind is from the south, the pack is concentrated or blown to the north. If the wind is from the north or west, however, ice can extend to the coast of northern Alaska. In winter the Chukchi Sea and the Bering Sea freeze over up to the region of the continental slope. The thickness of the ice and the amount of hummocky-ice depend upon the severity of the winter weather and changes in wind direction and strength. In the Bering Sea the ice thickness varies from a few inches to a few feet. Off northern Alaska the water freezes to a depth of 5 to 8 feet, but hummocking will increase this depth several fold.

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EFFECTS OF A TECHNOLOGICAL CHANGE IN AN ALEUTIAN VILLAGE†

Gerald D. Berreman*

This paper describes the way in which a change in one aspect of the economy of a small and isolated Aleutian village has affected the culture of all its members. The village is Nikolski, a community of 56 Aleuts on Umnak Island. The information upon which this paper is based was gathered during the summer of 1952 when the writer was a member of a small party of anthropologists, led by W. S. Laughlin, who resided in Nikolski. The party was supported by grants from the Arctic Institute[1] and the Graduate School of the University of Oregon.

In the past, Aleut livelihood was, in typical Eskimo fashion, almost entirely dependent upon the plentiful products of the sea. Among the most important of these were sea lions, seals, and salmon. Kayaks, now called *bidarkies* by the Aleuts, were fundamental to this maritime economy. The richly varied technology also included throwing boards, which were used to propel a variety of harpoons to secure sea mammals, and weirs, fish-spears, and hooks and lines for fishing.

A remarkable degree of economic security was achieved through the use of all available resources, and by a combination of self-sufficiency within the family and community-wide cooperation and sharing. Thus every man was capable of securing his own sea lions, but every sea lion catch was shared throughout the village. To some extent this situation still exists today.

The Russians, who first contacted the Aleuts in 1741, were quick to realize the value of their skills. They put the men to work hunting sea otter throughout the islands and as far away as Siberia and California. This resulted in tremendous hardship and, together with massacre and disease, led to depopulation and the disappearance of many villages. , In those villages which survived, however, the traditional economy continued. Rather than trying to make the Aleuts adopt their customs, the Russians encouraged them to keep their own village life[2], and in many ways it was the Russians who adapted themselves to the local culture, living in and depending upon the Aleut villages for their needs.

With the purchase of Alaska in 1867, the United States also acquired the Aleutians, but changes were few until after the turn of the century. Then the economic situation began to alter rapidly, with serious effects throughout the Aleut culture.

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[1]With funds provided by the U.S. Office of Naval Research.

[2]An exception was in religious matters. The Aleuts adopted the Russian Orthodox Church in the 1820's, and that church remains today a focal point of village interest.

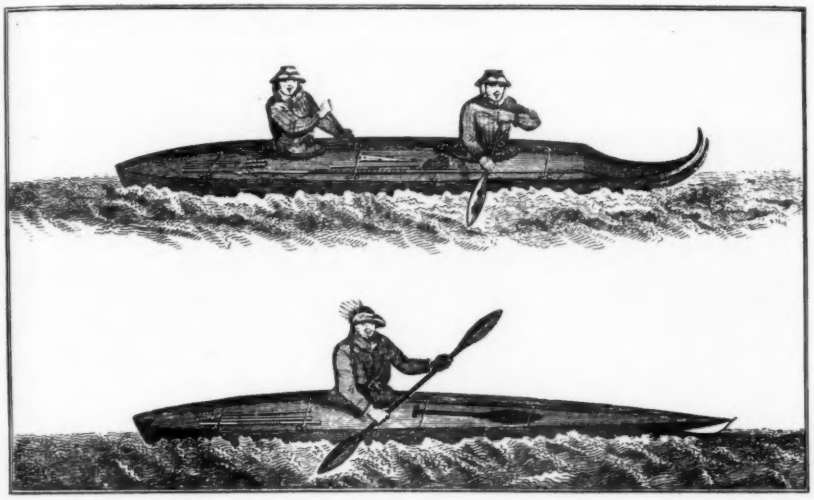

Fig. 1. Aleut bidarkies outfitted for hunting (from 'A voyage to the Pacific Ocean' by Capt. James Cook and Capt. James King, 1784, facing p. 112). The two-man bidarky may have been a post-Russian innovation.

These effects and their interrelationship can be illustrated by taking one very specific and fundamental technological innovation—the change from the traditional bidarky, the one-man skin boat, to the large wooden dory, which was introduced by the Americans and is exclusively used today—and showing its ramifications in the community culture of Nikolski. This transition has come about within the last forty years, and proceeded most rapidly during the 1920's.

Dories proved to be simpler to maintain and operate than bidarkies; they were larger, sturdier, and had a greater carrying capacity. They were especially useful in transporting hunters, equipment, and furs when fox hunting was profitable, as it was in the 1920's. Furthermore, the dory was approved by the white man, while the bidarky was ridiculed. Today only a few of the older men know how to handle a bidarky, and fewer still (two or three, by Aleut estimate) know how to build one. Only one bidarky existed in the village in 1952, and it had long been unused.

An immediate effect of this change from bidarky to dory was an alteration of the basic hunting patterns. The dory, by its very bulk and clumsiness, was largely responsible for a decline in the use of valuable offshore fishing and hunting areas, for which the small, light and manœuvreable bidarky had been ideally suited. The throwing-board and harpoon were rendered almost useless by the noise and size of the dory which kept sea mammals at a distance. Instead, the rifle, long used in addition to traditional weapons, came to be relied on exclusively for procuring game. This contributed to dependence upon the outside economy and to decreased use of the immediate local resources, which have probably been the most far reaching of the effects of the bidarky-to-dory shift.

Fig. 2. Aleut dories, Umnak Island, 1952.

The bidarky was made entirely of local products, such as driftwood and sea lion skins, which every man could obtain for himself. Construction and repairs required skill and diligence, but not outside help. Dories, by contrast, are made from commercial lumber, and those now in use have all been imported ready-made. Six of the eight dories in the village in 1952 were powered by ponderous, single-cylinder gasoline motors. In order to utilize the marine economy today, a man requires money to buy, maintain, and operate a boat. This is only one of the many reasons for wanting money, but it was one of the earliest and most urgent. Now, every male over fifteen years of age has a wage-paying job for part of the year. These are, with few exceptions, summer jobs at the government sealing station in the Pribilof Islands. While there, the men miss the summer fish runs and the best hunting and wood-gathering weather in Nikolski. They therefore miss the opportunity to make use of the local natural resources which were traditionally the basis of the local economy.

During the summer months the Aleuts formerly camped in family groups away from the village on sites which offered especially favourable opportunities for hunting and fishing. Summer labour outside has reduced this activity from a regular and economically essential pursuit to an occasional vacation outing, which has lost its importance as training in the traditional ways of life.

In the summer time the women and children are now left in the village with few men for their support. The stability of the family is adversely affected by the absence of men and by resulting changes in household membership. Women who are left alone at the beginning of the summer move in with friends or relatives for the three-to-six-month period. The few men who do remain in the village must spend most of their time supplying the daily needs of the community. Consequently, little preparation is made for winter,

and the money of the returning labourers becomes essential for survival later on. Hence, money is as necessary as are the dory and rifle it maintains. Only a combination of the unreliable cash income and the marine economy keeps the village going, neither alone being sufficient as a sole source of livelihood.

The combination of local and outside resources has not been a happy one. In the past fifty years the village population has decreased by half. Poor health and low morale, both at least partly resulting from economic insecurity, have contributed to lowering the birth-rate and raising the emigration rate. These changes may also be seen in the outlook and behaviour of individuals. Personal conflicts, at a minimum in other phases of Aleut life, are prominently associated with money matters, even when connected with such a cohesive force as the church. Decreased cooperation and community responsibility in general are often commented upon by elder villagers, one of whom said, "Now, people want money for everything". Recently, community sharing of the salmon, which are communally seined, has given way to sharing among only those who participate in the seining. The seine keeper remarked, "Now, that is the only way we could get them down to help. Everyone would rather let the other fellow do it than pitch in and help". Similar comments and changes in procedure could be cited in several other activities.

These changes have resulted in decreased community identification and loss of traditional controls, and the acquisition, by young people, of goals associated with money—goals which are attainable only outside the village. These include expensive equipment and American foods, clothing, recreation, and education. The introduction of the dory hastened this dependence upon money.

Childhood training, and therefore transmission of the culture as a whole, was also altered significantly. Formerly a boy underwent intensive training from infancy for adult responsibilities. He was taught, for example, to sit with his legs straight in front of him in preparation for the bidarky, and to bend his arm properly to propel the harpoon from this position. From the age of about ten years, he began to spend most of his time with his father or another man, acquiring the complex skills and knowledge necessary to survive and obtain a living in a bidarky. At about fifteen years he could hunt alone, and by the age of eighteen he could have his own bidarky. Girls were trained to outfit a man and his bidarky for the sea. During the long training period, children learned not only the skills necessary to livelihood; they were also taught the proverbs and legends, the *mores* and values, the ideal and actual behaviours which constitute Aleut culture. Traditional controls were thus instilled in the children and the largely informal social structure was handed down.

With the advent of the dory and rifle, youngsters could learn the necessary skills in a fraction of the former time. Careful tutoring was no longer a necessity. It became important to prepare for work outside even before becoming competent with the dory, so that money could be earned with which to buy the new-found necessities. In 1922, when intensive bidarky training was coming to an end, an American school was established in the village.

Children then spent even less time with their elders. As a result of decreased traditional training, knowledge and skills necessary to make use of many local products were irretrievably lost to Nikolski. The younger generation also failed to acquire much of the rest of the community culture which they would have learned incidentally from their tutors. Behaviours, values, and goals shifted to those advocated by the school teacher and were associated with the new and foreign culture. The gravity of this situation to the community is shown by the fact that in 1952 every child over nine years of age planned to emigrate from the community as soon as possible. Several have already gone. The reasons given invariably indicate a desire to be successful in the white man's way of life.

Patterns of social structure and behaviour in the village have also been affected. Individualism, in one of its most important forms, was eliminated when the dory was adopted. Two men (or a man and boy) are needed to operate a dory, and four or more to launch and beach it each day. A bidarky, in contrast, was a one-man craft. With it, a man was a free agent who could secure a livelihood for himself and his family alone, if necessary. Now he must depend on others for help. Furthermore every man owned a bidarky, whereas only one out of three men can afford a dory. Those without must depend upon the generosity of the dory owners, and are at a social and economic disadvantage. The prestige a man formerly derived from a fine bidarky of his own making has been replaced by the prestige of possession of a good dory, obtained with money. Today it is not the most able, in the Aleut sense, who have the best means to obtain a livelihood and prestige; it is those who have spent the most time outside and so have acquired money and its material benefits. Respect for the older men has suffered; they no longer have the best equipment and give the most useful advice. They are out-of-date, and they are monetarily poor. Their role as tutors, sources of knowledge, and authorities on behaviour has been impaired, with serious effects upon social controls.

The position of the village chief himself, traditionally a respected leader of village affairs, is threatened. His authority is challenged by young people who have been successful in the new economy, and who have won the approval of the powerful white men in the village—the school teacher, who represents the Government, and the sheep-rancher, who legally owns the village lands. Some of these young people are on the government-sponsored "village council" which conflicts with the chief in authority on village affairs. Community stability has been weakened by friction between this group and the more traditionally-minded villagers who support the chief.

Another social change has been in the status of women. Women have long had a role decidedly subordinate to that of men in Aleut society, but the acquisition of the dory has intensified this. In the past women performed one vital function connected with the sea and hunting: that of sewing the cover on the bidarky. Now they have nothing to do directly with the dory. The women also used to gather most of the wood for fires. Today the spacious dory can transport it much more efficiently. These factors, plus the ability

of men to buy their clothes, have lowered the female status, and may have contributed to the present postponement and even decrease in incidence of marriage. One Aleut said, "The reason this village is going down is that the men don't marry and raise families. Too many stay single". Perhaps wives are no longer as essential as they used to be, although economic insecurity has also made family life less attractive.

The ramifications of the bidarky-to-dory shift are thus abundantly evident throughout the culture. It is important to note, however, that acceptance of the dory cannot be said to have been directly causal in all cases. It is often virtually impossible to determine a clear cause–effect sequence in such a context. Nevertheless the adoption of the dory has contributed significantly and was responsible for many of the changes described here.

Oscar Junek said of a somewhat similar situation in an isolated Labrador community, ". . . the adoption of some of the modern mechanical equipments (e.g., one-cylinder gasoline motor) which help the isolated folk community system to pursue its fishing techniques with much greater facility than before the introduction of such articles . . . [does] not affect the precepts or *mores* of the social system."[1]

It seems more likely, in the light of the example presented here, that such innovations do vitally affect the less tangible aspects of community life, but not as directly or obviously as they affect the economy. It is improbable that any cultural compartment is as watertight as Junek's statement implies. Certainly in Nikolski all changes appear to provoke other changes.

The bidarky-to-dory shift has helped transform the culture from the traditional cooperative, independent, and secure village, to one of individual dependence upon unreliable, outside resources. Since the outside resources cannot be satisfactorily obtained and used within the community, emigration has increased and the village appears to be disintegrating. If it were possible to provide a cash income which could be fully utilized to satisfy the Aleut's wants within the village, the future might be brighter. This is suggested by the fact that among Aleutian villages today an inverse ratio apparently exists between village stability and prosperity, and the distance from the mainland, and therefore from the source of money and goods.

[1]Junek, Oscar W. 1937. 'Isolated communities: a study of a Labrador fishing village'. New York: American Book Co., p. 130.

A NOTE ON ARCTIC OCEANOGRAPHY AND THE LOMONOSOV RANGE

W. G. Metcalf*

In the article by Clifford J. Webster on "The Soviet expedition to the Central Arctic, 1954", published in this number of *Arctic*, the Russian discovery of the Lomonosov Range and their efforts at mapping and studying the implications of the range have been described.

It may be pointed out that the existence of this submarine range has been inferred and, indeed, actually observed in part by American scientists in the course of studies in the Arctic Basin since 1951. It is interesting that scientists of the two countries working, apparently, from entirely different approaches arrived at identical conclusions concerning this underwater feature.

During ice landings with aircraft north of Alaska in April 1951, Crary *et al.* (1952a) found the ocean basin in the Beaufort Sea to have a depth of 3,838 metres at 74°45N., 150°55W. Worthington (1953) recorded a depth of 2,950 m. about 300 miles north of this point in March 1952. From the oceanographic data gathered by Worthington, the deep water in the Beaufort Sea was shown to be warmer by 0.35°C than that in the ocean north of Siberia and Svalbard as described by Nansen (1902) and Sverdrup and Soule (1933).

Worthington believed that this could be explained in one of two ways: either the deep water entering the Arctic Basin from the Norwegian Sea has warmed up since the earlier observations were made, or "there is a submarine ridge, running roughly from Ellesmere to the New Siberian Islands, which separates the deepest water of the Beaufort Sea from the remainder of the basin". Favouring this latter explanation, Worthington predicted from his oceanographic data that the sill depth of the ridge would not be more than 2,300 m. He was not able to estimate how shallow it might be.

Later in 1952, Crary *et al.* (1952b) reported that in the drift of the ice island T3, a sea mount or part of a submarine mountain range was crossed at 88°N., 161°W. which rises from an ocean basin between 3,750 and 3,900 m. deep to within 2,900 m. of the surface. Other sharp rises from the ocean floor were noted, but as the depth was measured only approximately twice a week from the island, it was felt that the maximum height of the ridge may nowhere have been observed.

Still more recently, Crary (1954) has constructed a bathymetric chart of that part of the Arctic Basin covered by the drift of T3 during the time geophysical parties were stationed on the island. A certain amount of extrapolation of the bathymetry beyond the limits of the actual drift was made

*Woods Hole Oceanographic Institution.

possible by the fact that the slope as well as the depth of the bottom was observed. The resulting chart shows a distinct submarine mountain range rising to within 1,400 m. of the surface in at least one place. This range was crossed and recrossed numerous times by the drifting ice island. These crossings took place between 87½° and 88½°N. and 75° and 180°W., so that the extension of the range towards Ellesmere Island at one end and the Novosibirskiye Ostrova (New Siberian Islands) at the other is, on the basis of these data, still mostly conjectural. Also, the true peak and sill depth of the ridge, even along the section of the ridge that has been shown positively to exist, cannot be accurately demonstrated by present data.

The Russians views on the surface circulation pattern in the Arctic Basin are also of interest. That a clockwise movement of the ice is present in the Beaufort Sea, has been mentioned by Stefansson and others who made early observations north of Alaska. Farther north, Worthington's oceanographic data disclose a well defined geostrophic current flowing along a clockwise path bounded on the east by the Canadian Arctic Archipelago. The submarine mountain range apparently forms another boundary to this circulation. The frequent crossing of this range by the drifting ice island could be due to local winds moving the ice back and forth as it follows the main circulation pattern.

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REVIEWS

MULTIPLE GLACIATION IN ALASKA.

By Troy L. Péwé *and others. Washington, D.C.: Geological Survey Circular 289, 1953. 10½ x 8 inches; 13 pages; table and folding map. Free on application to Geological Survey, Washington 25, D.C.*

This is the first major research contribution applying the modern concepts of glacial chronology to sufficient of the vast territory of Alaska for the arctic specialist to begin formulating a complete picture of its glacial history. The eight field studies included in this report represent detailed reconnaissance during two to four warm seasons each; although the correlations are purely tentative, the archaeologist may start to see what the evidence is for a mid-Wisconsin interstadial time with intermontane corridors even more free of ice than at present. The biologist will find indications of four widespread ice advances of decreasing magnitude, after each of which a complete repopulation has occurred. He should not forget, however, that lesser advances, like the minor advance described in the "late Wisconsin", may have intervened between these major glaciations. The soil scientist will recognize evidence for rather long warm intervals between the "pre-Wisconsin" and "Wisconsin" glaciations and once again within the "Wisconsin".

None of this evidence is given in great detail, nor are there detailed maps, for this is a progress report. However, the nature of the evidence and the region in which each clue is found is clearly shown.

The Pleistocene geologist will find a two-fold division of major Wisconsin ice advances: (1) more than 18,000 years before the present, and (2) between 8,000 and 14,000 years before the present. As with recent radiocarbon dates in Illinois, Indiana, and Ohio, these may imply some readjustment in the timing and naming of Wisconsin substages. Could a 20,000-year-old glaciation really be early Wisconsin equivalent of Tazewell? If "early Wisconsin", as used here, correlates with Cary substage, one wonders what happened in Alaska during the conventional earlier Wisconsin time. It may be possible that certain substages in Alaska expanded while others diminished due to precipitation changes. The maxima of glaciation might not then coincide with those in central North America. Perhaps one or two of the "pre-Wisconsin" stages based upon "very subdued end moraines" are actually the very early Wisconsin, just like the old Iowan in the United States. Frank admission of the uncertainties in these eight studies should prove an inspiration to further work.

It is surprising that in seven of the eight areas examined extending from the Brooks Range to the Alaska Peninsula, there is real evidence of one or more pre-Wisconsin glaciations. In some, there is glacial erosion above the level of later moraines, in others, till lies far beyond the confines of later moraines and dissection or loess cover indicate antiquity. Although the separation into two pre-Wisconsin glaciations may be questioned, there can be little doubt of at least one.

This report is an outstanding example of the cooperation and integration possible when independent studies in widely separated areas are carried out under one agency. It exhibits the value of frequent interchange of ideas during field study rather than the domination of Detterman, Fernald, Hopkins, Muller, Karlstrom, Krinsley, Péwé, and Wahrhaftig by any one man. The advantages of good air photos and air transportation can be seen. It is also heartening to see such basic scientific spadework coming from far-sighted expenditure of some military funds.

Richard P. Goldthwait

CLIMATOLOGICAL ATLAS OF CANADA.

Prepared by M. K. Thomas. *Ottawa: Department of Transport, Meteorological Division, and National Research Council, Division of Building Research, 1953. (N.R.C. No. 3151; D.B.R. No. 41). 12 x 9 inches; 256 pages; charts, tables, and graphs. $2.00.*

Climate is one of the most important influences on building in any country. When it was necessary to revise the National Building Code of Canada, first published in 1941, a section dealing with climate was planned. As the work developed it was seen that many more charts would be useful than could possibly be included in the National Building Code. The 'Climatological atlas of Canada' is a joint undertaking of the Meteorological Division, Department of Transport and the Division of Building Research, National Research Council; it was prepared by M. K. Thomas, of the Canadian Meteorological Service, who has been working with the Division of Building Research. The atlas contains not only the twelve charts included in the revised code, but also all the other charts prepared in this basic study of Canadian climate in relation to building problems. The atlas gives a broad coverage of climatic variations throughout Canada, and is useful in fields other than building. Isopleths for most of the climatic elements have been carried into the Arctic.

The eighty-two charts and tables are grouped into nine sections, under the usual climatic headings, plus sunshine and insolation, seismological disturbances, and permafrost. Short, well-edited explanatory notes precede each section of charts, and similar texts accompany each chart. The layout is well planned, and it is a pleasure to be able to read the note and study the chart without having to turn the page.

In the section on temperature it is interesting to find, apart from the standard definitions, a series of charts showing winter design temperature, "the coldest temperature which is likely to recur frequently enough during the average winter to justify its use in the design of heating systems for structures". Similarly, summer design temperature charts, dealing with heat instead of cold, give an unusual picture of temperature conditions throughout the country. A beautiful illustration of temperature conditions in Canada is given in Chart No. 1-22, "Mean annual total degree-days". A degree-day is a unit based upon temperature difference and time. It is used by fuel-oil companies in estimating fuel consumption. In Canada the increase in the number of degree-days from south to north is quite marked, showing the combination of the severity and the duration of the winter season in the different latitudes. Other charts show the extreme lowest recorded temperature and the mean of the lowest temperature each year, over a number of years. These charts reveal that the northern parts of the Prairie Provinces, Yukon Territory, and central Quebec have mean annual minimum temperatures as low as arctic Canada, and that the absolute lowest temperatures recorded in many settled parts of the country are as low as those in the Arctic. However, the time element is not considered in these records, as it is in the degree-day chart, where winter, as a combination of low temperature and long duration, is clearly demonstrated to be dependent on latitude and distance from the sea.

The section on wind is also well planned and instructive, especially the unusual "Computed maximum gust speed" charts. The only additional information one could wish for is some indication of windchill. Charts showing the combination of wind speeds with air temperatures throughout the country at the various seasons would have helped to illustrate the cooling, which, in certain regions, affects human beings and mechanical equipment intensely.

The atlas is really more than a 'Climatological atlas'. It contains a table showing the total possible duration of sunlight on the 15th of each month for latitudes 40°N. to 85°N.; it has a series of tables showing the altitude of the sun

at various times of day on the 21st of each month for different latitudes; it includes a very interesting chart of earthquake probability, and a section showing hythergraphs. Hythergraphs are diagrams, devised by Dr. Griffith Taylor, to show in a twelve-sided figure the mean precipitation and mean temperature of a chosen location for each month of the year. The atlas contains hythergraphs for the largest cities of the country and for representative locations in northern Canada; hythergraphs for London, Paris, and Washington have been included for comparison. In Dr. Taylor's 'Canada' there is a "comfort frame" showing the values of temperature and precipitation for a place with a "comfortable climate", (comfortable for people of middle latitudes; tropical peoples and Eskimo have different standards). It would have been interesting to see this "comfort frame" included in the atlas for it would emphasize how far most of Canada's climate is from "comfortable".

The atlas is a beautiful production at a surprisingly low price and deserves to be widely used.

SVENN ORVIG

ELECTION OF FELLOWS

At the Annual Meeting of the Arctic Institute held in Montreal on 20 November 1954 the following were elected Fellows of the Institute:

Dr. Colin Bertram, Scott Polar Research Institute, Lensfield Road, Cambridge, England.

Prof. J. B. Bird, Department of Geography, McGill University, Montreal, Que., Canada.

Dr. Charles E. Bunnell, College, Alaska.

Col. N. A. C. Croft, Scott Polar Research Institute, Lensfield Road, Cambridge, England.

Dr. Christian T. Elvey, Geophysical Institute, College, Alaska.

Gerald FitzGerald, U.S. Department of the Interior, Washington 25, D.C., U.S.A.

Col. J. O. Fletcher, U.S.A.F., Air University, Montgomery, Ala., U.S.A.

Dr. George O. Gates, U.S. Department of the Interior, 4 Homewood Place, Menlo Park, Calif., U.S.A.

Dr. E. H. Grainger, 3485 University Street, Montreal, Que., Canada.

T. A. Harwood, Arctic Section, Defence Research Board, Ottawa, Ont., Canada.

Dr. William S. Laughlin, University of Oregon, Eugene, Ore., U.S.A.

Dr. E. N. Patty, University of Alaska, College, Alaska.

Dr. L. O. Quam, Geography Branch, Office of Naval Research, 990 North Tuckahoe St., Falls Church, Va., U.S.A.

G. W. Rathjens, P.O. Box 317, Berkeley, Calif., U.S.A.

Dr. Brian Roberts, Scott Polar Research Institute, Lensfield Road, Cambridge, England.

Mrs. Diana Rowley, 10 Maple Lane, Ottawa, Ont., Canada.

Dr. Ivar Skarland, University of Alaska, College, Alaska.

Dr. William C. Steere, Stanford University, Stanford, Calif., U.S.A.

Andrew Thomson, Meteorological Division, Department of Transport, 315 Bloor St. W., Toronto, Ont., Canada.

Dr. R. C. Wallace, 4 Centre St., Kingston, Ont., Canada.

Prof. Mogens Westergaard, Universitetets Genetiske Institut, Universitetsparken 3, Copenhagen, Denmark.

Dr. I. L. Wiggins, Department of Biology, Stanford University, Stanford, Calif., U.S.A.

ARCTIC RESEARCH

THE CURRENT STATUS OF RESEARCH AND SOME IMMEDIATE PROBLEMS IN THE NORTH AMERICAN ARCTIC AND SUBARCTIC

ISSUED AS **ARCTIC,** VOLUME 7, NUMBERS 3 AND 4
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DIANA ROWLEY

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Photo: Canadian Army

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Folding map

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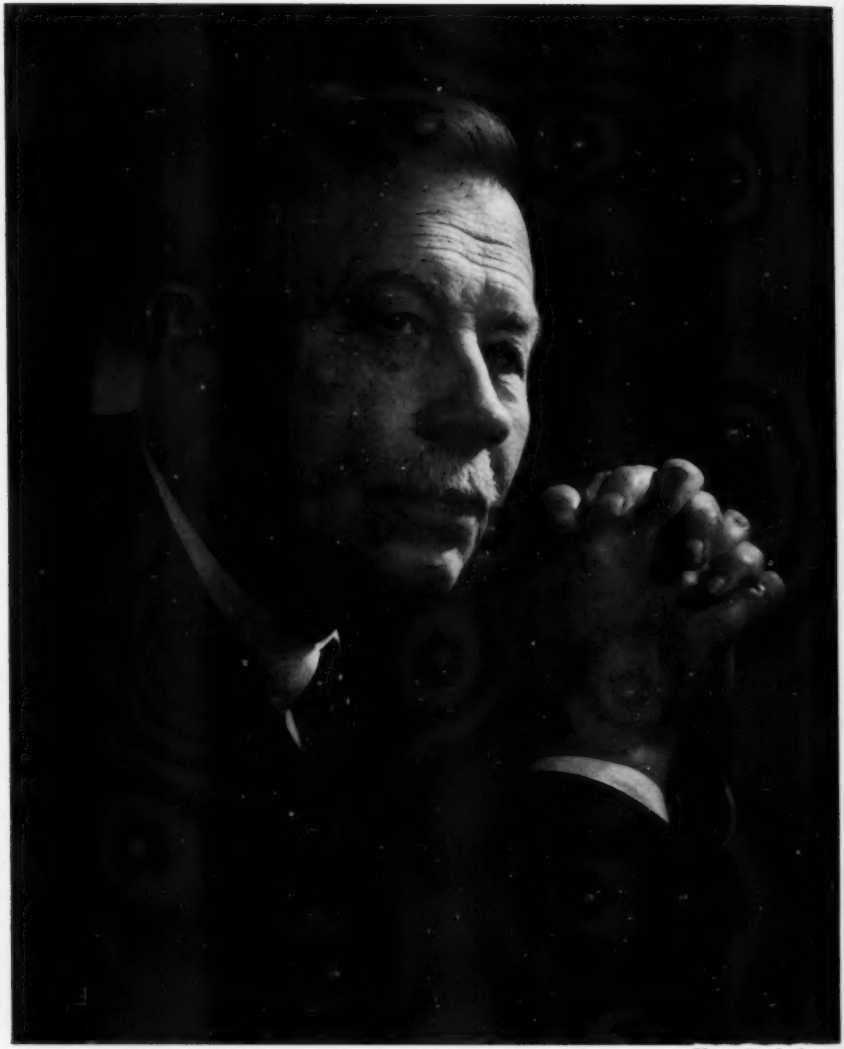

Photo: Karsh, Ottawa

R. C. Wallace, Executive Director, Arctic Institute of North America, from November 1951 to January 1955.

INTRODUCTION

R. C. Wallace*

THE Arctic Institute of North America is concerned with the prosecution of research in the arctic and subarctic regions of the North American continent and in Greenland. The United States, Canada, and Greenland are represented on its Board of Governors. In the ten years during which the Institute has functioned, it has financed, or helped to finance, 177 projects of research in these northern areas, in a great variety of fields of scientific endeavour. In so doing, it has assisted in building up a corps of younger scientists competent to work in arctic territory. From these younger men much will be expected in the future. For the need is great.

There are other agencies that are responsible for research work in the far north—governmental departments, private corporations, industrial firms. But the Arctic Institute of North America is the only agency that is international in scope. It deals with the problems in their wider scientific importance, unimpeded by national boundaries. Not only is this in the best interests of science; it is also in the best interests of international cooperation. There are common problems of defence in which this northern territory plays a very significant part. Because of this fact, a part of the research work in the Arctic in recent years is on the classified list, and does not appear in the current publications. It is none the less of great importance both from the scientific standpoint and in the national interest.

The Research Committee of the Arctic Institute felt that a review of the present status of arctic research in the various fields of science would now be of value both to the scientific worker and to others who are interested in northern development. It was suggested that there would be great value if the present trends and the future needs were emphasized. The Committee has been fortunate in securing the cooperation of highly competent authorities in the sciences that are represented in this volume. The reader will be impressed with the work that has been accomplished. He will be even more impressed with what yet has to be done. The territory is very large. Much of it is not easily accessible. The season in summer is short. The work is arduous and demands special training. The workers are relatively few. This volume will have served its purpose if it stimulates to more widespread activity in arctic research. What has already been done has added greatly to our knowledge of the Arctic. It has done more; it has made the Arctic more accessible to those who are engaged in the development of its resources, and in the well-being of its people.

*Executive Director, Arctic Institute of North America, from November 1951 until his death in January 1955.

The Arctic Institute of North America has already played no inconsiderable part in the encouragement of arctic research. Governmental departments, corporations, and private individuals have assisted the Institute greatly in their work. It is a great pleasure to take this opportunity to express the appreciation of all who are associated with the Institute for the support which has been given so generously. It is the hope of the Governors that, with still wider support, much can be accomplished that the authors of the papers in this volume feel is so urgently needed to be done.

Dr. Wallace was the moving spirit behind this volume until his death on 30 January 1955. As now completed, it is a tribute to his initiative and leadership.

EDITORIAL NOTE

The papers in this volume have been written during the past three years. Most have been brought up to date, but there are a few which have not been changed since they were completed. No attempt has been made to cover every scientific field in the volume, or to restrict the papers to the same geographical region. The authors were left free to deal with their subjects as they wished, and this has naturally resulted in a wide variety of subject and approach. On behalf of the Board of Governors I would like to express the gratitude of the Institute to all those who have written papers for this volume.

A great many people have given much of their time in advising on the material and providing information for the volume and I wish to thank them for their generous assistance. Special mention must be made of the following: Dr. H. S. Bostock, Mr. T. H. Manning, and Dr. A. E. Porsild, who have studied all the manuscripts; the Deputy Minister of Mines and Technical Surveys, Mr. Marc Boyer, who authorized the preparation of the folding map; Mrs. J. G. H. Halstead, who assisted in the preparation of some of the papers; and Mrs. E. F. Roots, who prepared the index.

DIANA ROWLEY, *Editor*
Ottawa, November 1955.

METEOROLOGICAL ACTIVITIES IN THE CANADIAN ARCTIC

R. W. Rae*

The establishment of a joint weather station by Canada and the United States on Cape Belknap, on the north coast of Ellesmere Island, in April 1950, marked an important milestone in the progress which is being made in our meteorological knowledge of the arctic regions of North America. This station was named Alert after one of the ships of the Nares expedition of 1875–6, which carried out the earliest exploratory work in this area.

Instrumental meteorological observations had been taken at a few isolated locations in northern Canada over one hundred years ago, for example, at the Hudson's Bay Company's Post at York Factory in 1772 and 1773. Numerous arctic expeditions also provided data, but these were only of limited use in meteorological research because they rarely extended over a period longer than a year for any one location. Moreover, observations at different locations were seldom taken during the same years, so that comparisons were difficult.

The need for permanent weather reporting stations in the Arctic was recognized in the earliest days of the Canadian Meteorological Service, but their establishment was a slow process owing to lack of funds, lack of communications, and the inaccessibility of these regions. Stations were established between 1900 and 1910 along the Mackenzie Valley as far north as Herschel Island. In the late 1920's government radio stations were opened at Aklavik, Coppermine, and other parts of the Northwest Territories, enabling northern observations to be transmitted rapidly to forecast centres in the south. During this period stations were also established by the Marine Radio Section in Hudson Bay and Hudson Strait to provide navigational aids to shipping and to take meteorological observations.

The most important and dramatic expansion of the weather station network in the Canadian Arctic has taken place since 1946. Five permanent weather stations, manned jointly by Canada and the United States, have been established on the Queen Elizabeth Islands, in the extreme north of the Canadian Arctic. In March 1952 a station was set up by the United States Air Force still farther north on the Ice Island T3,[1] and observations were transmitted regularly until May 1954. At that date the ice island, which appeared to be drifting along the same path it had travelled previously—

*Canadian Army Operational Research Establishment, Defence Research Board of Canada (formerly Head of Arctic Section, Meteorological Division).

[1]For an account of our present knowledge of the origin and paths of travel of ice islands, *see* Koenig *et al.* (1952).

Fig. 1. Weather reporting stations in northern Canada.

clockwise towards the 180th Meridian and then northwards over the pole towards Ellesmere Island—was lying near Alert and was therefore abandoned.[1] It is hoped that these ice islands, which are believed to originate from the Ellesmere Ice Shelf, will make it possible to maintain semi-permanent weather stations in the Polar Basin and to fill a considerable gap in our knowledge.

By September 1955 there were as many as forty-one weather stations operating in the Canadian Arctic and Subarctic between 58°N. and 82°30N. (*see* Table 1 and Fig. 1).

Use of meteorological observations

Meteorological observations are used mainly for three purposes: the preparation of synoptic charts, the compilation of climatological summaries, and physical research. As soon as an arctic station is established, and has made radio contact with a main collecting station such as Resolute, its observations are immediately used in the preparation of synoptic charts at forecast centres throughout the northern hemisphere. Arctic observations have been found to be especially useful in the construction of work charts for long-range forecasting, such as the five-day and thirty-day forecasts that are issued regularly by the U.S. Weather Bureau.

[1]A small United States party reoccupied the ice island in April 1955 on a temporary basis, but meteorological reports were not transmitted. *Ed.*

Table 1. Weather reporting stations in northern Canada, September 1955

Station	*Latitude*	*Longitude*	*Altitude in ft.*	*Types of observations*	*Year first surface obs. made*
Aishihik, Y.T.	61° 39N.	137° 28W.	3170	SH	1943
Aklavik, N.W.T.	68 14	135 00	30	SIPR	1926
Alert, N.W.T.	82 30	62 20	205	SIPR	1950
Arctic Bay, N.W.T.	73 00	85 18	36	SPR	1937
Baker Lake, N.W.T.	64 18	96 05	30	(S)(I)PR	1946
Cambridge Bay, N.W.T.	69 07	105 01	47	S(H)P b)	1928
Cape Hopes Advance, P.Q.	61 05	69 33	240	SI b)	1928
Chesterfield, N.W.T.	63 20	90 43	13	SIP	1921
Churchill, Man.	58 45	94 05	115	SHPR b)	1884
Clyde, N.W.T.	70 27	68 33	26	SPR b)	1942
Coppermine, N.W.T.	67 47	115 15	13	SR	1930
Coral Harbour, N.W.T.	64 11	83 17	193	S(H)PR	1933
Dawson, Y.T.	64 04	139 29	1062	S(H)	1898
Ennadai Lake, N.W.T.	61 08	100 55	1065	SI	1949
Eureka, N.W.T.	80 00	85 56	8	SIPR	1947
Ferguson Lake, N.W.T.	62 52	96 49	400	(H)	1953
Fort Chimo, P.Q.	58 05	68 25	117	SHPR b)	1921
Fort Providence, N.W.T.	61 20	117 40	547	S	1942
Fort Reliance, N.W.T.	62 43	109 06	539	SH	1948
Fort Resolution, N.W.T.	61 10	113 41	549	S(H)b)	1914
Fort Simpson, N.W.T.	61 52	121 21	415	SIP	1897
Fort Smith, N.W.T.	60 01	111 58	665	SHPR	1913
Frobisher, N.W.T.	63 45	68 33	68	SHPR	1942
Hay River, N.W.T.	60 51	115 46	529	SH	1893
Holman Island, N.W.T.	70 30	117 38	30	(S)	1940
Isachsen, N.W.T.	78 47	103 32	83	SIPR	1948
Mayo Landing, Y.T.	63 35	135 51	1625	S(H) b)	1927
Mould Bay, N.W.T.	76 17	119 28	50	SIPR	1948
Norman Wells, N.W.T.	65 18	126 51	240	S(H)PR	1944
Nottingham Island, N.W.T.	63 07	77 56	54	SI	1928
Padloping Island, N.W.T.	67 06	62 21	130	SIP	1941
Port Harrison, P.Q.	58 27	78 08	66	SIPR	1921
Port Radium, N.W.T.	66 05	118 02	600	S(H)	1942
Resolute, N.W.T.	74 43	94 59	209	SIPR	1947
Resolution Island, N.W.T.	61 18	64 53	127	SI	1928
Snag, Y.T.	62 22	140 24	1925	SH	1943
Spence Bay, N.W.T.	69 31	93 27	55	(S)	1951
Teslin, Y.T.	60 10	132 44	2300	SH	1943
Watson Lake, Y.T.	60 07	128 48	2248	SHP	1937
Whitehorse, Y.T.	60 43	135 05	2289	SHPR b)	1904
Yellowknife, N.W.T.	62 28	114 27	682	SHP	1942

Symbols:
- b) Broken record.
- P Pilot balloon or rawinsonde observations.
- R Radiosonde observations.

Surface observations are made and transmitted as follows:
- S At the principal synoptic hours (0030, 0630, 1230, 1830 GMT).
- (S) At some but not all of the principal synoptic hours.
- I At the intermediate synoptic hours (0330, 0930, 1530, 2130 GMT).
- (I) At some but not all of the intermediate synoptic hours.
- H Hourly throughout the 24 hours.
- (H) Hourly during part of the 24 hours, or on request.

Although the density of weather stations in the Arctic has steadily increased in recent years, there are still many gaps at strategic points where the establishment of a weather station would aid materially in the preparation of synoptic charts for the far north. For instance, a station on Melville Island, which has no observation stations within a radius of 250 miles, would help explain such problems as the westward penetration of the moist polar–Atlantic air masses. These air masses, which are much milder than the adjacent arctic air, are sometimes pumped over the Eastern Arctic islands as far west as Resolute by winter storms in the Davis Strait area.

A station on the south coast of Melville Island, in the vicinity of Winter Harbour, was included in the original plans for the network of joint Canadian/United States arctic weather stations, and a cache of prefabricated building components and fuel was made near Bridport Inlet in the summer of 1951. However, because the U.S. Weather Bureau was unable to obtain funds for participating in this project, and because there was insufficient demand for the station to warrant its installation by Canada alone, it was decided in January 1954 to abandon the plan. Nevertheless, a weather station is being established by Canadian agencies on the west coast of Banks Island in the near future.

Climatological records

A minimum of ten to fifteen years of records is necessary for the determination of representative climatic means. Observations from many stations in the Canadian Arctic are clearly inadequate in this respect. Nevertheless, their records have already made it possible to correct climatic charts for this area. For example, temperature observations from Eureka station indicate that the "cold pole" for North America lies in northern Ellesmere Island rather than on the mainland west of Hudson Bay, as previously supposed (Rae, 1951).

The network of stations in the Arctic is too sparse to permit filling in the variations caused by local factors. Some of these variations may be of considerable magnitude, especially in the vicinity of areas like the North Water in Smith Sound, where open water persists throughout the winter. A useful general study of the effect of ice and open water distribution on the winter climate of the Eastern Arctic has been completed by Hare and Montgomery (1949), but the effect of the North Water on the winter temperatures of adjacent land areas requires further investigation.

All the weather stations in the arctic islands are located on the coasts and therefore additional temperature records are needed farther inland. It is likely that temperatures in the interior of the larger islands are somewhat higher in mid-summer, and lower in mid-winter than temperatures near the coast. Some idea of the possible extent of this effect is provided by the records from Pond Inlet, which lies in a sheltered valley, where the average monthly temperatures in winter are about 10 degrees lower than those at Clyde, on the open coast. The occurrence of extremely low winter temperatures in sheltered valleys is especially marked in the Mackenzie basin and the Yukon. For example, the lowest temperature that has been recorded officially in Canada, -81.4°F, occurred at Snag Airport in the Yukon in February 1947.

Upper air observations

In recent years the emphasis in meteorology has been shifting from surface observations to a study of the atmospheric processes at higher levels. A thorough knowledge of upper air conditions in polar regions is essential in order to complete the three-dimensional picture of atmospheric motions over the earth as a whole. Upper air soundings are taken regularly at almost all weather stations in the Canadian Arctic.

An excellent summary of northern Canadian aerological data was prepared by Henry and Armstrong (1949), and now needs to be supplemented with more recent observations from the joint arctic weather stations. Some progress is being made in this regard by the Canadian Meteorological Service with a summary of radiosonde data for all Canadian upper air stations, which will be published shortly.

Observations for air operations

The shortest air routes between North America and many parts of Europe lie across the Canadian Arctic, and several such routes were used to ferry aircraft during the Second World War. Commercial aviation companies are also beginning to take an active interest in the development of transpolar air routes, and both the Scandinavian Airlines System and Canadian Pacific Airlines have commercial flights across the Canadian Arctic on a routine basis. Observations from the arctic weather stations are essential for these operations. The Research Section of the Canadian Meteorological Service is at present analysing and summarizing upper wind data so that frequency distributions of flight times can be obtained for a given route and a given aircraft. The extension of the method to transpolar routes will be possible as soon as sufficient upper wind data are available from the Canadian arctic stations.

Extensive air operations over the Arctic will entail the use of many arctic stations as staging points or alternate landing fields, and will thereby create a demand for terminal forecasts for these stations. Arctic weather forecasting during the summer months does not present insuperable problems to a meteorologist trained in temperate latitudes. In winter, however, when frontal activity in the Arctic is very slight, and the weather is greatly influenced by local factors, an intimate knowledge of the topography and local wind regime is essential in order to determine the frequency of ice fog and blowing snow, which are the two main causes of reduced visibility.

Ice fog studies

Extensive analyses have been made by the Canadian Meteorological Service of the occurrence of low temperature fog at Canadian stations, including those in the Arctic. These analyses have been chiefly climatological in order to determine the physical principles involved.

In general terms, the results obtained so far indicate that the probability of fog decreases as the temperature drops from 32°F to about –20°F. Below –20°F there is a gradual increase in probability, which becomes more rapid as the temperature drops below –30°F. For temperatures below –40°F, ice crystal fog is almost certain to occur, although it may not be of sufficient density to affect air operations. Visibility at the ground is usually greater than one mile in ice crystal fog, but visibility from the air may be limited to the vertical.

Blowing snow

Blowing snow is almost inevitable during arctic winters whenever the surface wind speed is greater than 15 m.p.h. Empirical methods have been

used at many forecast stations to relate visibility in blowing snow to the speed of surface wind. In 1947–9 at Resolute it was noted that for winds below 15 m.p.h. blowing snow was limited to ground drift, and visibility was generally over 6 miles. As the wind increased above 15 m.p.h., more and more snow particles were whirled aloft with a corresponding reduction in visibility, until at speeds over 30 m.p.h. the visibility was less than one-half mile. At moderate wind speeds, the severity of blowing snow for a given wind speed was not constant from day to day. This variation might be explained by the difference in the degree of binding among the crystals forming the snow surface. Further observational data concerning snow surface conditions are required to evaluate the magnitude of this effect.

Research in arctic meteorology

Observations of the various meteorological elements both at the surface and in the upper air are being steadily accumulated from the arctic stations to provide data for research. It is self-evident that before research can be carried out on any problem it is necessary to begin with accurate observations, as any inaccuracies in the basic data will tend to invalidate the results obtained. For this reason a large proportion of arctic meteorological data must be treated with caution, for some meteorological elements cannot be measured accurately in the Arctic. The elements which present the greatest problem are humidity, snowfall, and, in winter, the amount and type of clouds.

There are many organizations in North America carrying out research in arctic meteorology. One such group is the Arctic Forecast Team, Meteorological Division, Department of Transport, at Edmonton, which is working mainly in the synoptic field. Dewar, Thompson, and Wilson, who are members of the team, and Markham, a former member, have published their results in a number of Meteorological Division circulars.[1]

Humidity

The ordinary hair hygrometer becomes inoperative at temperatures lower than about –20°F, and is therefore useless throughout most of the arctic winter. Moreover, the difference between readings taken with wet- and dry-bulb thermometers at low temperatures is generally so small that the observer cannot detect it, and often arbitrarily manipulates the readings to give a difference of 1/10 of a degree. There is no need to elaborate on the worthlessness of such observations, and yet winter humidity observations are published for many arctic stations that are not equipped with any other humidity measuring devices than a hair hygrometer and wet- and dry-bulb thermometers.

A frost-point hygrometer has been developed, which can measure the absolute humidity of very dry air at temperatures as low as –90°C (Brewer *et al.*, 1948), but it is too complicated for routine use at weather stations, and none of the Canadian arctic stations are equipped with it. The Instrument

[1]See references.

Section of the Canadian Meteorological Service is working on the development of a visual type of dew-point apparatus which may also be used at low temperatures. A small thermistor is inserted into the surface of the instrument just below the dew observation button. The deposit on the button is observed through a fixed magnifying glass, and the sampled air is pumped on to the surface through a jet, and cooled by expanding CO_2 from a bottle through another jet just below the button. Rate of cooling may be adjusted by a needle valve which regulates the escape pressure. Extensive tests indicate that the instrument is satisfactory for routine use, and although it is expensive to manufacture, it is hoped that some of the Canadian arctic stations can be supplied with one in the near future.

Snowfall

Measurements of snowfall at arctic stations are often rendered inaccurate by drifting. Other inaccuracies are likely to occur in published figures of arctic precipitation when conversion is made from snow to an equivalent amount of rain. The most widely used conversion factor is ten inches of snow to one inch of rain. This ratio is approximately correct for newly fallen snow in temperate latitudes, but for arctic regions, five inches of snow to one inch of rain would be a closer approximation.

Cloud type and amount

Cloud observations must be made indirectly during the winter dark period when the moon is not up. The presence of clouds is assumed when stars are not visible in any section of the sky, and the height and type can usually only be guessed. Nevertheless, the low-powered ceiling projectors recently installed in some of the arctic stations are proving helpful in increasing the accuracy of observations.

Permafrost studies

Perennially frozen ground underlies the greater part of the Canadian Arctic, and undoubtedly exercises considerable influence on the climate of the region. The Arctic Forecast Team is already carrying out a study of the meteorological aspects of permafrost, but further investigations are needed.

Jet streams

One of the most striking advances to be made in meteorological research in recent years was the discovery of a narrow zone of extremely strong winds in the upper troposphere. This belt of high winds, which has been given the descriptive name of "jet stream", is usually associated with the polar front, but there is evidence to indicate that a jet stream may also be associated with the arctic front at times. For example, Greenaway (1950, p. 3) has made the following observation: "The strongest wind encountered was in February, and had a speed of 118 kts. blowing from the NNE at 12,000 feet about 40 miles off the north coast of Borden Island. At the time light to moderate turbulence was encountered and a layer of cloud extended up to flight level. Wind velocities measured at half-hour intervals on either side of this wind

were not greater than 45 kts. This exceptionally strong wind has many of the characteristics of a jet stream and may be due to similar causes. At the time there was an extensive low over the eastern part of the archipelago, and as far as I can judge from the available data, the arctic front was probably fairly far north. We may have here an indication of a jet stream associated with the arctic front and the absence of previous evidence of this phenomenon may be simply due to the meagre upper air records in high latitudes".

Studies of the structure and behaviour of jet streams at high latitudes are being pursued by the Research Section, Canadian Meteorological Service, by means of cross-sectional analyses of selected situations. In particular, an attempt is being made to determine the relationship, if any, between such jet streams and fronts in the Arctic (McIntyre and Lee, 1954).

Ozone

The basic meteorological observations consist of temperature, pressure, humidity, and wind. The radiosonde and rawinsonde are the main tools of synoptic meteorologists for determining these properties from the surface to high levels. However, more and more attention is being focused by research meteorologists on other types of observations, which may throw additional light on meteorological problems.

Ultraviolet radiation from the sun in the wave length band 2,200 to 2,900 A is absorbed in the upper stratosphere. It has been demonstrated that the absorbing agent is ozone, and its total amount above a station may be measured by means of an instrument known as a Dobson spectro-photometer. Changes which occur in the ozone spectrum provide information about the height of the centre of gravity of the ozone layer and also the nature of the vertical distribution curve.

Although there are day to day variations in the amount of ozone above any station, the average amount has been observed to increase with latitude from a minimum at the equator to a maximum at high latitudes. According to Craig (1950, p. 10), the ozone maximum occurs at a latitude between 45° and 60°N., with a gradual decrease farther poleward, except perhaps in the spring. However, very few observations have been made north of latitude 70°, and observations from a place such as Alert, near latitude 82°30N., would provide valuable material for further study.

The importance to meteorology of research on atmospheric ozone results from the fact that the ozone content of the air appears to be relatively stable, and that day to day variations in the amount of ozone in any one place are caused largely by advection or turbulence. For this reason, ozone observations may provide a means of studying air circulation at high levels, and aid in completing the picture of the general circulation of the atmosphere.

At present there is only one Dobson spectro-photometer in Canada, and it is located at Edmonton. An instrument at one of the weather stations in the Archipelago would assist materially in exploring the potentialities of routine ozone observations in weather forecasting, and be of great value in high latitude observations.

Radiation measurements

In arctic regions the annual outgoing radiation is greater than the incoming radiation, whereas in tropical regions the reverse is true. Since there is no evidence to indicate that the Arctic is getting progressively colder and the Tropics progressively warmer, there must be some mechanism which provides for the exchange of heat between the Arctic and the Tropics. If the net radiation loss in the Arctic and the net gain in the Tropics were accurately known, a computation could be made of the magnitude of air transport required between the Arctic and the Tropics to maintain equilibrium conditions.

Very few radiation observations have been made in the Canadian arctic islands, though some solar radiation measurements are being made at Resolute. Moreover, measurements of the temperature profile in the lower layers of the air at Alert, and soil temperatures at Resolute, provide additional material for radiation studies. It is hoped to extend the scope of the present radiation measurements by installing a long-wave radiometer at Resolute in the near future.

Studies on the relationship of solar radiation, visibility, sunshine duration, and vertical distribution of humidity are being made by the Canadian Meteorological Service in order to be able to predict the daily amount of insolation at any specific location, and to prepare charts of monthly mean solar radiation, as well as mean clear-day radiation amounts, for all Canada. Theoretical studies of long-wave radiation are also being carried out, which will eventually be applied to determine fluxes and cooling rates, and to interpret radiation measurements in the Arctic.

Night sky radiation and aurorae

The general structure of the upper regions of the atmosphere has been surmised from many different types of observations such as meteors, night sky radiation, and aurorae. Experiments have been carried out in several countries on the measurement of night sky radiation (Hulburt, 1951). Observations have been taken as far north as 63°, and from the data, it was concluded that on nights when aurorae were not present, the brightness of the sky did not vary because of changes in latitude. It would be of interest to carry out a series of observations during the polar night at a station as far north as Alert, to determine whether these results apply to the arctic regions as well.

Detailed auroral investigations have been made in Norway, but such investigations in the Canadian Arctic would be of special interest owing to the proximity of the north magnetic pole. A limited series of auroral observations was begun for the Radio Physics Laboratory of the Defence Research Board at Alert, Eureka, Isachsen, and Mould Bay, in the fall of 1952.

Canadian responsibility in arctic meteorology

In view of the extent of the Canadian sector of the Arctic, Canada shoulders a heavy burden of responsibility for the maintenance of weather stations in the Arctic. This responsibility has been accepted, although the

expense of establishing and maintaining stations in isolated arctic locations is vastly greater than in more settled areas. The joint program being carried out by Canada and the United States in the arctic islands is a splendid example of international cooperation. It is providing a means for obtaining extensive meteorological and other scientific data, which will be available for research at centres throughout the world.

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RESEARCH IN GEOLOGY AND GEOMORPHOLOGY IN THE NORTH AMERICAN ARCTIC AND SUBARCTIC

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THIS paper defines, in general terms, the status of research in the north in geology and geomorphology, and reveals some of the limitations to present knowledge in these fields.

The authors are grateful to those who have assisted them. Thanks are due particularly to Y. O. Fortier, J. M. Harrison, and C. S. Lord of the Geological Survey of Canada, and to George O. Gates, George Gryc, Troy L. Péwé, Clyde Wahrhaftig of the U.S. Geological Survey, and to Thomas G. Payne formerly of the U.S. Geological Survey.

Geological mapping

Of first importance in the understanding of the geology of any region is the availability of adequate geological maps. Ideally such an understanding develops from the exploratory, through the reconnaissance, to the detailed stage. In the North American Arctic and Subarctic this pattern broadly applies, but the six great regions, Alaska, Yukon, Mackenzie, Keewatin, Ungava and Franklin each present special problems owing to their diversity in character. Because of this it is not feasible to adhere everywhere to the ideal pattern, and individual variations are necessary to facilitate more rapid coverage with maps of practical scales and standards for the different terrains.

In Alaska, the Yukon, and the Cordilleran parts of Mackenzie, the system is fairly standard. Exploratory, reconnaissance, and detailed mapping are in progress, though at different stages of completion. The exploratory geological mapping, usually published on a scale of about 1:500,000 or smaller, is perhaps 60 per cent complete in Alaska and in the Yukon. It is followed by reconnaissance mapping using scales of about 1:250,000, and for this some 38 per cent of Alaska and 15 per cent of the Yukon have been covered. More detailed maps on scales from 1:63,360 to 1:12,000, and occasionally on even larger scales, are made of selected areas.

In the unforested parts of the Precambrian areas of Mackenzie and Keewatin geological mapping is following a somewhat different course. In 1952 "Operation Keewatin", undertaken by C. S. Lord and others of the Geological

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Survey of Canada, introduced a new method of Canadian reconnaissance mapping. By use of helicopters and supply aircraft 57,000 square miles were methodically traversed for geological maps on a scale of 1:500,000 and, where it seemed desirable, interesting localities were examined in greater detail. This method of mapping is being applied to all suitable terrain where it is filling the role of both exploratory and reconnaissance mapping of bedrock and Pleistocene features. From its results areas for more detailed mapping will be selected. In the forested areas of these districts, largely in Mackenzie where the aerial technique is less suitable or impracticable, the system of mapping is similar to that used in Alaska and the Yukon; and some 16 per cent of these areas have been completed on a reconnaissance scale of 1:250,000.

In Ungava, which is largely forested, the exploratory mapping has been taken over by companies holding great concessions, and the government work has concentrated on reconnaissance mapping. The Labrador Trough region is being covered first, and about 10 per cent of Ungava has been mapped on a scale of 1:250,000 and more detailed mapping of selected districts is also in progress.

For Franklin, the plan is similar to that for the open areas of Mackenzie and Keewatin and coverage with maps on a scale of 1:500,000 is the first objective. The work was first begun with boats for transport in the field, but in 1955 "Operation Franklin" was carried out almost entirely with helicopters and supply aircraft over a huge area in the Queen Elizabeth Islands. No mapping on the reconnaissance scales is planned, but detailed maps of selected areas are contemplated.

Most of the geological mapping in the north has been of bedrock. In the past few years, however, some minor attention has been paid to the mapping of surface deposits, and the need for such mapping must be emphasized in view of the development that is underway or planned in the north.

In the last ten or twelve years, mapping programs have been accelerated by the development of modern methods, instruments, equipment, and transportation, and by the increase of general interest in the north. Among the new "tools", the use of air photographs is of paramount importance, and has done more than any other development to enhance the speed, accuracy, and completeness of mapping on all scales.

In general, while geological mapping in the Arctic and Subarctic, and the compilation and release of information have been and will probably continue to be the responsibility of government surveys, certain work is nevertheless suitable for other groups. In particular, the fields of local studies and mapping, and of research on topical problem studies, which always includes some mapping, may be mentioned. Some notable contributions to geological mapping have already been made by companies, and various agencies in papers, periodicals, books, and maps. But as a rule, companies have no desire to make their work public, although a few in Canada have turned over their general results to the government for publication. A notable instance is the 'Canol geological investigations', largely the work of the Imperial Oil Company Limited, compiled by G. S. Hume and T. A. Link, and published in Paper

45-16 of the Geological Survey of Canada. The recent condition for grants of large prospecting concessions in Canada, that copies of the geological maps and reports of the companies be given to the government within a specified period is expediting mapping by non-governmental groups.

Geological processes

Like geological mapping, the study and interpretation of geological processes peculiar to, or of special importance, in the north offers a most fruitful and much neglected opportunity. It should, of course, be kept in mind that processes such as ore deposition and vulcanism can be studied more effectively in temperate and accessible regions, although there will always be special instances when research on these two processes will have to be carried on in the north.

Under the rigorous climate of the Arctic and Subarctic, both chemical deterioration and mechanical disintegration differ from these processes in more temperate areas. This difference is due in part to frequent temperature changes, which cause materials near the surface to move back and forth from below to above the freezing point of water. The transportation of released material has not yet been investigated in the systematic fashion it deserves. More thorough studies should be made, for example, of the effects of rapid fluctuation and frequent overloading of glacial streams, the sediment contributed by the abrasive action of glaciers, and the transportation of material by floating ice on rivers as well as on the sea, the drying of surface materials in relatively arid areas as a result of the lowering of the permafrost level, the rapid growth of plants that form the mat-like tundra vegetation in the long, warm, summer days, severe and repeated frost action, low evaporation, and many other factors. Frost action is one of the most important geological processes in cold areas; some work has been done in the laboratory, but quantitative study in the field is needed.

Of special importance in the north is the mass wasting of material through such means as solifluction and rock glaciers. Some qualitative investigations have been made in these fields but there is specific need now for quantitative data, for example on rate of movement and angle of slope. The rate and type of soil formation would also be significant. Data could be gathered from carefully selected, easily accessible localities without great cost. As might be expected, the deposition of material is also widely different from the better known pattern in lower latitudes. This difference obtains on land and in streams, lakes, and the Arctic Ocean.

Large annual icefields are developed along many of the major rivers of the Arctic. The ice of such fields is sometimes referred to as "aufeis", and the process as "glacial icing". The literature is not clear as to just how such icefields form, how they grow, or the nature of their annual cycle. Some of these fields are large, 50 square miles or more, and their study would combine the application of geomorphology, hydrology, and related subjects.

Permafrost

A better understanding of the various phenomena of permafrost would be immediately useful in construction and development projects in the north. The English-speaking countries have made a late start in systematic investigations of permafrost, although considerable opportunity is available in North America to study geological processes controlled or modified by permafrost. Some work has been done in the investigation of such processes. For instance, R. E. Wallace and R. F. Black in Alaska have studied lake modification. Physiographic phases of the floodplain have been studied in permafrost areas, and the processes controlling them have been worked out by T. L. Péwé on the lower Yukon River, and the results applied to other large rivers in interior Alaska such as the Kuskokwim, Koyukuk, and Tanana. Processes important in the development of thermokarst topography have also been partially studied, and ice wedges have been examined in some detail. Accurate temperature measurements of frozen ground, including long- and short-term fluctuations, are now being made, and have been discussed by G. R. MacCarthy and M. C. Brewer. The origin of permafrost, however, has scarcely been touched upon.

Glaciology

In general, glaciation and glaciology in North America can be studied most effectively in the Subarctic ranging into the temperate zone but some work in the Arctic is essential. Substantial progress and much interest in these large fields have recently been shown by a number of groups, especially in Alaska and the Yukon, but much more remains to be done. In particular, research is needed on the glaciers and icefields of the north and on all the circumstances of their existence throughout postglacial time, before a proper grasp can be obtained of the many variable factors which lead to the presence of glaciers and to the phenomena associated with Pleistocene glaciation. In conjunction with these studies, work on glacial processes, including the physics of ice, is needed. A complete plot of all the northern glaciers, including the present boundaries and past stages, and extending back as far as possible in geological time, would also be valuable.

The Arctic and Subarctic of North America contain excellent fields for glaciological research in the western Cordillera and the eastern and northeastern islands. On the west there are the numerous great valley glaciers of the Alaska Range, the various coastal ranges, and the St. Elias Mountains. The larger glaciers, which have their sources in the icefields of these great ranges, flow outward in nearly all directions to regions of very different climates. Those moving southward are subjected to the relatively even temperatures and nourishing high precipitations of the coast in contrast to those passing northward into the semi-arid interior climate with its extreme temperatures. In these ranges, too, every variety of alpine glacier from the small, isolated individuals in cirques to great branching, many-headed, valley glaciers exist. It seems likely that the study of the distribution of the small glaciers and

groups of glaciers in northern Alaska, the Yukon, and western Mackenzie may shed light on the local microclimates, recent climatic changes, and geological history. The recent development of these regions, with the accompanying improvements in transportation, has brought a number of glaciers within the reach of modestly financed expeditions, of which many will be required in the future, since each glacier commonly requires individual study.

Northeast of the Mackenzie Mountains, the nearest glaciers and icefields are those of the eastern and northeastern Arctic Archipelago, where they are scattered over the areas east and north of an arc extending from Meighen Island, through Devon Island, to Cumberland Peninsula on Baffin Island. These glaciers, lying largely in latitudes well north of those on the western mainland of the continent, have environments of their own, and some appear to be thriving in areas which, in the light of present knowledge, receive inadequate precipitation for their existence.

In Alaska, the study of glacial processes has been receiving increasing attention. The early reconnaissance work done by Capps, Moffit, Smith, and others who studied glacial deposits incidentally to bedrock geology, has given way to a new phase in which the glacial deposits of broad areas have been mapped by Detterman, Fernald, Hopkins, Karlstrom, Krinsley, Muller, Péwé, Wahrhaftig, and others, and the information has been brought together by Péwé for publication. A glacial map of Alaska comparable in quality to the 'Glacial map of the United States', is now being compiled, by tying together by means of airphoto interpretation the areas where study has been completed.

In the Canadian north the study of Pleistocene and glaciological phenomena is increasing. This trend is due partly to the growing realization of the economic importance of the region, and also to the fact that the new topographical maps and air photographs are making information expressed by surface features more readily obtainable for large and remote areas. In the Yukon, much attention is being paid to the study and mapping of overburden, glacial phenomena, and general surface features both in the glaciated and unglaciated regions, but this work is still second to the mapping of the bedrock geology. In the other districts to the northeast the same is true. In 1952 the Geological Survey of Canada allotted a specialist to "Operation Keewatin", to devote his entire time to Pleistocene and surface geology, and this practice is expected to be continued for similar operations in the future.

Some problems of soil formation in different parts of the Arctic and Subarctic are closely associated with glaciation. Great differences, for instance, are apparent between the well developed soils of the large Yukon valleys between 60° and 65°N. latitude and the general lack of soil in central Ungava at about 55°N. The study of the factors contributing to this difference may show that the two regions have had different climatic histories since the close of the Pleistocene epoch.

The investigation of the origin and movement of loess provides a great opportunity for studying processes related to glaciation. Alaska, particularly, and the southwestern Yukon, with their active, braided, glacial streams and outwash plains, offer excellent fields for such studies.

Stratigraphy and structure

The geology of an area cannot be fully interpreted or correlated with that of other areas without understanding the geological succession in the stratified rocks, their structure, and their relationships within the area and with other areas. Over much of the North American Arctic, knowledge of the stratigraphy and structure is fragmentary, general, and only broadly useful.

The nature of the major geological structures in Alaska is fairly well known, and many details of the structural geology of a few areas, such as much of the Arctic Slope, have been studied. Over most of Alaska, however, structural detail has not been worked out. Such details are needed both for local application, and for helping to fill the gaps in current knowledge of the major structural patterns. Modern air photographs of Alaska are expected in the near future to lead to major advances in understanding the structural geology of the Territory.

Regional studies by specialized stratigraphers and paleontologists are particularly needed. The value of such work can readily be seen in the recent and very important contribution to knowledge of the Jurassic and Cretaceous systems in Alaska made by Ralph Imlay of the U.S. Geological Survey. One particularly important part of Alaska requiring study is the area along the international boundary between the Yukon River and the arctic coast. This, and studies of some other areas, might well extend across national boundaries, and include reviews of Siberian literature.

Detailed paleobotanical collecting and research, including spore studies, are needed to solve some Cretaceous and Tertiary problems in Alaska. For example, gently deformed Tertiary sections containing coals of low rank, as in the Kenai and Little Susitna districts, have in the past been assumed to be equivalent to more strongly deformed Tertiary sections containing high-rank coal beds, as in the Matanuska Valley area. It is now believed that the latter rocks, which are approximately conformable with Cretaceous strata, are older, possibly Paleocene, and may unconformably underlie the large areas of the less deformed beds, which in turn may be Eocene. The solution of this problem by paleobotanical studies, supplemented by test drilling, is important because of the shortage of bituminous coal in Alaska.

Detailed micropaleontological studies of Mesozoic formations in Alaska are also needed. Mesozoic rocks generally contain few megafossils, but recent age determinations by micropaleontological methods of Mesozoic rocks in northern Alaska have shown what could be done if such work were extended throughout the Territory.

In the Yukon and the Cordilleran part of Mackenzie, many aspects of stratigraphy and structure await further study. For example, much of the Yukon Plateau consists of metamorphosed, stratified rocks, referred to as the "Yukon group", of which the age, succession, and structure present a multitude of problems. Not only does the altered condition of the rocks make the solution difficult, but their concealment by overburden and by younger rocks, and their interruption by many intrusions frequently prevent the tracing of marked horizons. The main problems are establishing the succession and

correlation within the group, and determining the age. These problems are followed by those of correlating the structure of infolded or downfaulted areas of somewhat similar rocks, which by slight differences of composition and metamorphism and, in some instances, the presence of organic remains, suggest a younger age. Recent work by H. Gabrielse of the Geological Survey of Canada, in northern British Columbia, close to the Yukon, has revealed excellently preserved Lower Cambrian fossils in strata apparently overlying a great thickness of metamorphosed sedimentary rocks. Farther north, similar strata occur in the Yukon group. Thus, while most of the Yukon group is generally believed to be Precambrian, some rocks included in it may be Paleozoic, while others may be divisible from the main part as late Precambrian.

In the mountains around the Yukon Plateau the Paleozoic is present nearly everywhere. To the northeast in the Mackenzie Mountains a relatively complete section seems to await study: the Paleozoic appears in considerable thicknesses and, though large gaps occur in the succession, all the major periods are represented somewhere.

The relationships of the Upper Paleozoic and the Mesozoic in the Yukon Plateau present a variety of problems. Determinable faunas of Carboniferous, Permian, Triassic, and Jurassic ages have all been found, but persistent fossil horizons are usually rare. Moreover the general lithological similarities, and the intermingled masses of volcanic materials, make the understanding of their stratigraphy and structure extremely difficult. The early Mesozoic, however, is relatively well represented with several fossil horizons, and is now being studied by E. T. Tozer of the Geological Survey of Canada.

The Upper Mesozoic marine strata are unconformably overlain by a great assemblage of coarse, continental, clastic, sedimentary rocks with small amounts of volcanic material interbedded. The upper part of this assemblage, the Tantalus coal measures, is dated by its early Lower Cretaceous flora, but the age of the lower part, generally considered to be Jurassic, is uncertain. The Tantalus measures are overlain by a huge mass of volcanic rocks very similar to those mixed with the earlier Mesozoic and late Paleozoic. An analysis of the stratigraphy and structure of this mass of strata presents many intricate and difficult problems particularly in view of the general lack of fossils in the Upper Mesozoic.

The late Mesozoic volcanic rocks and the Tantalus measures are invaded by granitic intrusions, and are truncated by the erosion surface on which the Tertiary rocks rest. The whole interval at the close of the Mesozoic in the Yukon is poorly understood. The volcanic rocks are grouped together on such uncertain bases as lithology and distribution, and show obscure or varied relationships with the different intrusions and older strata. Determination of the succession, structure, and history of these rocks and their correlation with events at the close of the Mesozoic and opening of the Tertiary are major problems.

The earliest Tertiary rocks in the Yukon are continental, clastic, sedimentary strata showing extreme variations in consolidation, and usually some

warping and faulting. They commonly lie in depressions or valleys of steep relief in the dissected surface of the older rocks. In earlier explorations their floras were dated as Eocene, but those found in recent years are placed in the Paleocene. As in Alaska, the correct dating and sorting out of the many basins of these rocks requires broad study.

The Tertiary sedimentary beds are overlain by volcanic rocks, scattered in large and small patches over the Yukon Plateau and parts of the encircling ranges. These rocks exhibit different relationships from place to place. In some localities they are tilted and truncated by the mid-Tertiary or later erosion surfaces. In others they are spread upon it, and elsewhere they lie at various levels of dissection in its valleys. The record of the Tertiary history of the Yukon contained in them awaits assembling from a regional study.

Much of the western Yukon escaped Pleistocene glaciation. Mapping has now traced the general outline of the irregular front of the ice during its last major advance. More than one advance is recorded in several widely separated localities, and the earlier movements in most cases are the more extensive. These advances have left a sequence of deposits that overlap the gravels and other deposits of the unglaciated region. Together, these phenomena contain an intriguing record of the geological events of the region from the present back into the Pleistocene, and perhaps to the late Tertiary.

In the northern Yukon there has been little exploration on the ground, but air photography has been particularly valuable in delineating the broad geological features. The Porcupine Plain is revealed as an area of relatively flat-lying rocks and few outcrops, while in the surrounding mountains thick sections are exposed where the upturned strata and remarkable open structures of the ridges around the borders resemble those of the Appalachians, and also of the Parry Islands in the Arctic Archipelago. Sections of Tertiary, Mesozoic, Paleozoic, and even Precambrian sedimentary rocks are known in the ranges of the northern Yukon. During 1953 much of this region was explored in a search for oil and metals, and new information on it is expected to be available shortly. But geological exploration is still in too early a stage to pick out problems.

East of the Cordillera in Mackenzie and Keewatin, exploration is still in a preliminary stage, but "Operation Keewatin" extended the knowledge of the Precambrian section, revealing that the areas of Precambrian sedimentary and volcanic rocks are larger than previously supposed, and that many members, previously regarded as Archean, are of Proterozoic age. The sequence of the Precambrian strata in this region presents many interesting problems.

In recent years the discoveries of large deposits of iron ore in Ungava have led to the detailed study of the stratigraphy and structure of the Labrador Trough and the search for areas of similar rocks in the surrounding region. In the northern or subarctic parts of Ungava such rocks have been discovered only in the northern extension of the trough to the west of Ungava Bay and in a belt extending from Wakeham Bay to Cape Smith. The correlation of the rocks of the trough with those of the belt, and again with those of the Belcher Island and Nastapoka Bay group are the main problems.

Franklin is less known than the other districts but the widespread pattern of the explorations dating back to the early nineteenth century forms the skeleton of a remarkably complete general picture of the region. Many of its chief geological features and problems are set out by Y. O. Fortier and R. Thorsteinsson in their important paper on the Parry Islands folded belt.[1] The platform of the Precambrian Shield, composed of old crystalline rocks mantled in part by Proterozoic strata, slopes generally west from the highlands of Baffin, Devon, and southeastern Ellesmere islands, and very gently north from the mainland. In the southern part its surface is characterized by broad undulations whose hollows contain wide basins of both Proterozoic and Paleozoic strata. As a whole the rocks become progressively younger northwestward passing from Proterozoic through Paleozoic to Mesozoic and Tertiary.

In the south, between the waters of M'Clure Strait and Viscount Melville and Lancaster sounds and the mainland, broad ridges of the Precambrian rocks separated by basins of Paleozoic strata present many interesting subjects for study in Precambrian succession and Precambrian–Paleozoic relationships. The Paleozoic sections of the basins also contain many problems. Northward, in a broad arc from Melville Island to the northeast coast of Ellesmere Island and northern Greenland, belts of folded Paleozoic and Mesozoic strata form the Innuitian Region, which presents numerous problems of stratigraphy and structure. Northwest of this region the geology is even less known, though Mesozoic and Tertiary rocks, including some of both extrusive and intrusive origins have been found.

The government surveys have expended much of their effort on stratigraphy and structure, and notable advances are anticipated in the next few years. Nevertheless, these are large and important fields, and ample room remains in them for appropriate attack by other research scientists. Many of the fields will involve work in areas which are relatively inaccessible and isolated by long distances, and are therefore expensive to operate in. Economy of cost and efficiency of effort can be greatly enhanced by close cooperation among workers interested in different branches of science and by the joint use of existing facilities.

Geomorphology

The geomorphology of arctic and subarctic areas has been attracting substantial attention over the last few years. Much of this work has been a by-product of other investigations, but some has been done for its own merit. At present the greatest need is for a better grasp of such processes as rock disintegration, transportation, and sedimentation. While geomorphology in the north has probably been receiving about as much attention as other aspects of geological research, it is unlikely that the field will be fully occupied either by the government agencies or by mining companies, although some work has been done by both.

[1]Fortier, Y. O. and R. Thorsteinsson. 1953. "The Parry Islands folded belt in the Canadian Arctic Archipelago". *Amer. J. Sci.* Vol. 251, pp. 259–67.

In appraising the need for additional geomorphological research in the Arctic it should be remembered that the validity of conclusions in this type of research frequently depends on adequate bedrock maps and adequate knowledge of pre-Quaternary stratigraphy. In Alaska, substantial advances in geomorphology have recently been made, especially through projects of the Alaska Terrain and Permafrost Unit of the Military Geology Branch of the U.S. Geological Survey. Areas in Alaska where geomorphological information is lacking or scanty, and in which little or no research to our knowledge is now being done include:

(1) The southern front of the Brooks Range. Investigations should be undertaken preferably in conjunction with geological mapping on the same scale as, and after the completion of, adequate base maps.

(2) The Ray Mountains and the Koyukuk River basin.

(3) The lower Yukon River area.

(4) The Alaska Range between the head of the Nushagak River and the upper Kuskokwim River area, and between the upper Kuskokwim and the McKinley tributary of the Kantishna River.

(5) The Wrangell Mountains and the basin of the White River. Much important information regarding the geomorphological history of Alaska could be obtained in this area, where early Tertiary tills and an almost complete Tertiary volcanic sequence are reported. Good base maps presumably will be available in a few years. The work should be done in conjunction with remapping of the bedrock on an adequate scale.

(6) The basin of the Fortymile River and other parts of the Yukon–Tanana plateau.

(7) The western part of the Susitna River basin. Geomorphological studies could well be made in conjunction with the mapping of the coal resources of the Tyonek area and the gold placers of the Peters Hills.

The following studies should throw more light on geomorphological history:

(1) A study of the Yukon–Tanana plateau with special reference to origin and date of deposition of gold placers. In the Fairbanks district work should concentrate on pre-Wisconsin history.

(2) Geomorphological reconnaissance of Alaska, primarily to work out the preglacial geomorphological development of the Territory. This would consist of (a) intensive review of the literature and reading of old field notes, followed by (b) discussions with field geologists of geomorphological problems and evidence in their areas, followed by (c) study of air photographs, testing and developing hypotheses gained in parts (a) and (b), followed by (d) one or two seasons of intensive reconnaissance along existing routes of travel, to check and develop hypotheses, followed by (e) one or two seasons of intensive helicopter-borne reconnaissance. This would be at least a 6-year project. Its immediate economic value is in connection with gold placers.

In northern Canada the study of geomorphology has received little attention. The essential need is for a better grasp of the working of geomorphological processes characteristic of the north. In the Yukon, on the

border of the region where arctic processes are active, the main features appear to owe their character to those processes normal throughout most of Canada, but surface features are, at least, modified by such arctic processes as solifluction. Eastward and northward from the southern Yukon, the processes of the Arctic become more important in their bearing on the development of land forms. In Franklin, particularly, they are at a maximum. Here the problem is first to recognize the relative importance of marine submergence, glaciation, and such distinct arctic processes as solifluction, which now commonly mask features of other origins. The less conspicuous processes too, require study. For instance, the effects of erosion by the hard, sandy snow, driven so continuously by the wind against the outcrops of the arctic deserts through long winters, solution of rock by the cold waters, and chemical decomposition of rock under arctic conditions, all need proper evaluation before arctic geomorphology can be fully interpreted.

Ground water and engineering geology

Up to recent years, the subjects of water supply and sewage disposal have not been considered pressing in the Arctic and Subarctic. Actually, such problems have always existed and have always been closely related to the health situation of both native peoples and white inhabitants. With the coming of larger settlements and military establishments to the north, these problems have become critical. Water-supply and sewage-disposal problems are shared by surface-water and ground-water specialists. Surface water is dealt with in the field of hydrology and hence is not included in the scope of this paper. Ground water lies clearly within the bounds of geology.

It now seems inevitable that ground-water geology must play an important role in northern development. Already some of the larger communities such as Anchorage and Fairbanks are facing serious water problems that may well be solved in large part by the further development of ground-water supplies. Ground-water research appears to be largely a responsibility shared by the government surveys and the communities involved. At least two systematic government studies have been made in this field in Alaska. One of these applies specifically to the Anchorage area, and the other is of more general scope applying to all permafrost areas, and emphasizing ground-water principles rather than ground-water conditions in specific areas. In addition, a preliminary report on permafrost in the Fairbanks area, which briefly considers ground water, has recently been declassified and made available to the public.

While ground-water principles, as generally understood, apply in large parts of the Subarctic, new principles and new factors need to be appraised for permafrost areas. Thus ground-water geology in the north is closely related to both the permafrost and the geomorphological fields.

The application of geology to engineering works of various kinds such as highways, dams, tunnels, and foundations, and to deposits of such construction materials as sand, gravel, and clay, has long been a useful practice. This type of geological work has come to be known as engineering geology. In

the past ten years or so the value of engineering geology has become increasingly appreciated until now it has assumed an important place in geological work.

The need for engineering geology is especially great in the Arctic and Subarctic. Here special problems of foundations for large structures and for such works as highways, dams, and airfields, are created by the presence of permafrost, by the thick ice that annually forms on streams and lakes, by severe frost action, by wide stream valleys, by great variation in stream flow, by floating ice, and by many other factors.

In Alaska, the U.S. Geological Survey has carried on a number of engineering geology projects; some of these were projects of the Military Geology Branch. An engineering geology study has been made of the Anchorage area. A study involving engineering geology has been carried on at Fairbanks and in the Dunbar vicinity west of Fairbanks. Similar studies have been made in a few other places and a few special projects have been carried on, such as the study of slide problems along the Nenana River gorge as related to railroad maintenance. A full-time engineering geologist has now been stationed in Alaska by the U.S. Geological Survey to work on principles needed in coping with highway and other pressing problems.

Engineering geology in the north shares with other branches of geology certain limitations imposed by inadequate knowledge of some geological processes. It is, however, a field which can make extraordinary contributions to northern development, and in which the governments must participate to a large extent. At present, the most pressing need is probably for research on the principles, whose application will then be the special responsibility of smaller government units, such as provinces, territories, and municipalities, and of private groups, such as contracting firms and mining companies.

The limits to present knowledge in geology and geomorphology have been emphasized throughout this paper, because an understanding of them is necessary for appraising the relative values of proposed research programs. In addition, the paper has pointed out some opportunities open to geologists in the Arctic and Subarctic; opportunities which are now far greater than the anticipated supply of geologists. The failure of universities to stimulate interest in northern research may be partly responsible for this scarcity of arctic geologists. Another factor may be the difficulties facing scientists in isolated northern regions. But the great demand for results from the north, and the opportunity for working in little-known fields where individual initiative is both required and rewarded should be ample compensation for any difficulties involved. It is hoped that this paper, although incomplete, may serve as a guide and stimulus to future geological and geomorphological research.

GLACIOLOGY

P. D. Baird* and R. P. Sharp†

A Brief Review of the Recent History of the Science. By P. D. Baird

The science of glaciology is scarcely a century old. For many years it was treated rather lightly, mostly by geologists who happened to be also enthusiastic mountain climbers. It took a long time for men to realize that to explain some of the phenomena of past glaciation and the problems of Pleistocene geology a deeper study of the processes of existing glaciers was necessary. This concept was stimulated greatly during the past thirty years by the now classical investigations of Hans W:son Ahlmann (1948) in several areas around the North Atlantic Basin.

It can be argued that wherever perennial snow and ice is found in the form of ice cap or glacier we have a glacial climate, hence all glaciers in any part of the world are "arctic". Yet it seems that there are important physical differences between glaciers in temperate latitudes and those in polar regions, and Ahlmann has divided them in his geophysical classification on the basis of temperature and consistency of the upper parts of the glaciers.

Thus although many problems in glaciology, particularly those dependent on long-term observations, can most easily be studied in accessible, temperate glaciers, there are still some questions which can only be answered in the polar regions where strongly negative temperatures prevail in the glacial ice and in the firn snow above it.

In the North American Arctic the geographical extent of all land ice has still to be properly delimited. This would now be possible from a detailed study of existing air photographs, and a tentative classification of the glaciers could be made with the aid of spot field checks.

In recent years there has probably been more glaciological activity in Greenland than in Alaska or Canada. In 1939 Ahlmann's work in the North Atlantic area carried him as far as Greenland, to the Frøya Gletscher in latitude 74°N. on the east coast (1941). Immediately after the Second World War P.-E. Victor began organizing the Expéditions Polaires Françaises, which resulted in their large-scale Greenland project of the summers 1948–51 and the winters 1949–50 and 1950–1. A tremendous amount of glaciological work was achieved (Cailleux, 1952), and new ideas about the Greenland Ice Cap were formulated. Seismic soundings have now shown that at many places

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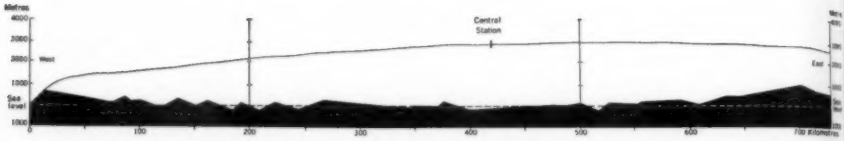

Fig. 1. The Greenland Ice Cap on a section approximately at 70°N., after the Expéditions Polaires Françaises 1948–51. From A. Joset reproduced by Cailleux (1952, p. 8).

the rock floor under the ice is at, or even below, sea level (Fig. 1). Based on these Greenland results J. F. Nye (1952) evolved a theoretical relationship between the thickness of an ice cap and its surface slope. By his calculations the rock floor in north Greenland, an area where British and American parties have recently operated, may be very greatly below sea level. We hope soon to have direct evidence on this point.

Next to Greenland Canada possesses most arctic ice, but until recently little glaciological work has been attempted. In 1950 the Arctic Institute's Baffin Island expedition investigated the Barnes Icecap (Baird *et al.*, 1951). This appears to be a relic of the Pleistocene age and is maintained chiefly by the refreezing of the annual meltwater on to the cold high Polar Ice, and not by normal accumulation of firn slowly changing to ice. There have been two further expeditions to Baffin Island. In 1952 a small party visited the Grinnell Glacier in southern Baffin Island, and in 1953 the Arctic Institute's expedition studied the Penny Highland, the second highest region of the Canadian Arctic.

Two other major projects in Canada should be mentioned. In 1952, under the direction of R. P. Sharp, a program of long-range investigation of many of the least known properties of glacial ice was started on the Saskatchewan Glacier, a readily accessible, temperate glacier in the Rocky Mountains. In 1953 G. Hattersley-Smith and R. Blackadar made a preliminary reconnaissance of the ice shelf off the north coast of Ellesmere Island in preparation for a joint Canadian/United States expedition the following year. This joint expedition spent the summer of 1954 making detailed studies of the shelf, which is believed to be the source area for the ice islands observed in the Polar Basin.

In the Alaska–Canada boundary area two large projects have been under way since 1948. The Arctic Institute, under the leadership of Walter Wood, has carried out work on the Seward–Malaspina system (Sharp, 1951), while the American Geographical Society has studied the Juneau Ice Field (Field and Miller, 1950). These projects were the first large three-dimensional surveys of glacial systems to be carried out in North America. On the Malaspina Glacier a bore hole 1,000 feet deep has been sunk, and inclinometer measurements should yield important results on glacial flow at depth. On the Juneau Ice Field core samples of ice have been obtained down to about 300 feet. Great fluctuations from year to year in precipitation and ablation have been recorded, and a start has been made in both areas on winter studies.

Recent North American work in the Polar Basin has largely concentrated on problems connected with ice islands. Since 1946 the existence of very

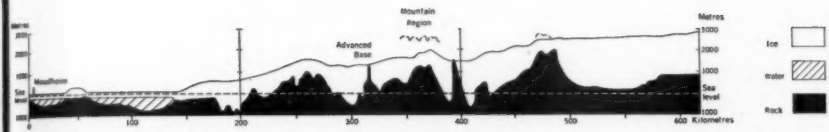

Fig. 2. The Antarctic Ice Cap on a section approximately southeast from Maudheim, after the Norwegian-British-Swedish Antarctic expedition. From Robin (1953, p. 57).

large stable ice masses floating in the Polar Basin has been known, and some of their tracks have been plotted by crews of the U.S.A.F. and R.C.A.F. (Koenig *et al.*, 1952). On 19 March 1952 the first landing was made on one of these ice islands, known as T3, in a position 103 miles from the north pole, and a semi-permanent base was subsequently established by the U.S.A.F. A program of scientific observations was carried out and regular weather observations were transmitted until May 1954 when the ice island was abandoned.[1] The thickness of T3 averages about 200 feet, and borings to 60 feet have shown a mainly freshwater origin, although at the lower limit there are traces of salt. There has been considerable Russian activity in the Polar Basin and some news of their work is just becoming available.

Outside the North American Arctic other glacial studies are being pursued and should be noted here because their evidence is essential in assessing such problems as "the warming of the Arctic". The Norsk Polarinstitutt now has a glaciologist on its staff who is responsible for investigations both in Norway and Svalbard. A clearly defined mountain glacier, Storbreen, and a swiftly moving tongue from Jostedalsbreen have been selected for continued study, as has Finsterwaldbreen in Vestspitsbergen.

In Iceland a glaciological society has recently been formed and has established a small research station on the Vatnajökull (*Jökull*, 1951).

Results from the large Norwegian-Swedish-British Antarctic expedition (Robin, 1952), in which a study of the glaciology of the antarctic continent was a principal consideration, have shown that the season 1950–1 was one of glacial equilibrium in Queen Maud Land and that there appears to have been no appreciable thinning of that section of the antarctic ice cap in the past decade. Seismic soundings showed over 2,000 metres of ice thickness inland, and borings were made with core examinations up to 70 metres deep on the ice shelf at the expedition base (Fig. 2).

From these widespread studies we are beginning to gain a picture of the extent of the recent rather alarming retreat of glaciers (*see* Figs. 3–6). This appears to be progressing violently in the European area and the Pacific coast, less violently in arctic North America, and scarcely, if at all, in the Antarctic.

The future, as R. P. Sharp points out, should lie with detailed examinations of selected accessible glaciers. At present there is tremendous activity on these lines in Switzerland. The volume of valuable detailed glaciological research carried out there probably exceeds that of the rest of the world.

[1] A small United States party reoccupied the station in April 1955, and planned to remain for the spring and summer months making scientific observations. *Ed.*

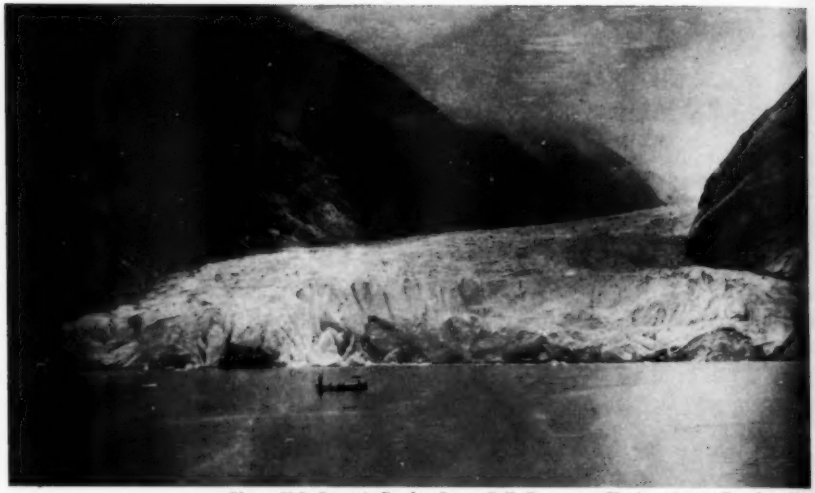

Photo: U.S. Coast & Geodet. Surv., Coll. Comm. on Glaciers, Amer. Geophys. Un.

Fig. 3. North Dawes Glacier, Endicott Arm, Alaska, in 1889, showing a party from the U.S. Coast and Geodetic Survey vessel *Patterson* which made the first determination of the position of the terminus of the glacier.

Photo: W. O. Field

Fig. 4. North Dawes Glacier in 1935, when the terminus had receded about 3,900 feet since 1889.

Photo: W. O. Field

Fig. 5. North Dawes Glacier in 1941.

Photo: Amer. Geogr. Soc.

Fig. 6. Valley of the North Dawes Glacier in 1950. Total recession from 1889 to 1950 was approximately 6,500 feet.

Most meticulous surveys have been made of some of the larger glaciers, and by means of tunnels, sponsored by hydroelectric concerns, much is being learned about internal structure of ice masses.

The polar explorer and scientist is intimately interested in the climate both present and past. The study of glaciers is one of the most valuable in the elucidation of climatic history. As we move back in time, glacial geology takes over from pure glaciology as the science concerned with collecting the evidence. We are back to the geologist again. But the fields of meteorology, physics, and botany have been drawn in, and the practical work of the engineer is required to assist the field investigator, who must still have a strong back and a love for snow and ice.

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Some Aspects of Glaciological Research. By Robert P. Sharp[1]

The following brief comments make no pretence at providing a complete survey of desirable research in glaciology. The aim is rather to "sign post" the beginnings of trails that might be followed by interested workers. These investigators must themselves become well informed on the basic principles, so they can independently evaluate the desirability of a specific program and determine the best means of carrying it forth. No one can or should try to tell someone else how to tackle a research problem. They can only indicate some of the areas that appear worthy of consideration, and that is the objective here.

Velocity relations in glaciers

Differential movements within glaciers, both in time and space, have been recorded for more than a century (Forbes, 1843, pp. 124–56). In view of this

[1]Contribution No. 666, Division of Geological Sciences, California Institute of Technology.

extended observation and the data obtained (Hess, 1904, pp. 115–50; Klebelsberg, 1948, pp. 80–9), it is truly surprising that so much remains to be done. Large, relatively untouched but highly promising areas of investigation in the field of velocity relations invite attack. For ease of discussion, differences in surface velocities are treated, first with respect to spatial relations and then with respect to temporal variations. This is followed by consideration of velocities at depth in glaciers.

Surface velocities: Many studies on different valley glaciers provide a reasonably good picture of velocity distribution along transverse profiles on the surface. More efforts should be directed toward obtaining data on velocities over the entire surface of the glacier, as only a little information of this type is available (Hess, 1904, p. 136). This will have to be done by means of carefully controlled measurements at a network of widely distributed points and not just along two or three profile lines. At the same time information should be obtained that will allow an evaluation of the influence on flow velocity of surface slope and channel characteristics, especially width and depth.

If velocity studies are possible only along profile lines, efforts should be focused on longitudinal profiles. Such data are of prime importance as a means of testing theoretical concepts bearing on extending and compressive flow in glaciers (Nye, 1952, p. 89). Little information is available on longitudinal velocity changes in North American glaciers (Matthes, 1946, pp. 222–5; Matthes and Phillip, 1943, p. 21). The situation is better for European glaciers (Hess, 1904, pp. 128–35, 148; 1933, pp. 37–8), but quantitative data are needed.

Nearly all measurements of surface velocity to date have recorded only the downvalley component parallel to the glacier surface. It has long been recognized that the absolute direction of movement is actually oblique to the surface and of different angles and different amounts from place to place (Hess, 1933, p. 41). The failure to build upon Reid's (1896, pp. 917–21; 1901, pp. 749–50) early work on this matter is a striking oversight, and this remains a promising and fertile line of investigation.

Variations of flow velocity in time constitute a closely allied subject for study. Although more and better quantitative data on seasonal velocity fluctuations would be useful, measurements over shorter periods provide an even more fruitful line of investigation. Such measurements must be carefully controlled or the data will be open to such question and uncertainty as to make them almost worthless. Some earlier investigations of short-period variations have not been rigorously controlled, and most, if not all, have been made with respect to a single station on the glacier surface. Indications are that the care and labour required to make reliable short-period measurements at a number of stations will be well worth the trouble. Preliminary studies on the Saskatchewan Glacier (Meier *et al.*, 1954, pp. 9–12), show that surprising and puzzling differences of velocity occur from day to day between stations located in the same flow-line as well as beween stations in different flow-lines. Adjacent flow-lines are not always coordinated in their periods of acceleration

or deceleration, and different parts of the same flow-line behave differently during the same interval. It seems that much can be learned about the nature of glacier movement from short-period observations of a number of points on the glacier surface.

Instances of exceptional acceleration and deceleration show a definite but unexplained correlation with major meteorological events, especially periods of precipitation. Much more field data on this type of relation must be gathered before even the crudest type of analysis from the standpoint of physical mechanics will be possible. Whether the erratic velocity behaviours involve some sort of wave movement within the ice, or whether the normal processes of flow respond directly and sensitively to variations in the meteorological elements cannot be determined on the basis of present information.

The movement of waves or surges through a glacier needs more study. Such surges have been recognized (Hess, 1931, p. 240, 1933, pp. 94–5; Finsterwalder, 1937, p. 99; Streiff-Becker, 1938, pp. 18–19; Klebelsberg, 1948, pp. 87–8), and one is currently progressing down the Nisqually Glacier on Mount Rainier in Washington (Harrison, 1951, p. 11). It is of utmost importance that these phenomena be carefully observed and their various behaviours recorded. An understanding of the mechanics involved would certainly further our knowledge of glacier flow. In addition, they are obviously important in causing erratic advances at the terminus of a glacier.

Glaciology, like many other phases of earth sciences, is currently passing from a stage of general observation to one of more careful quantitative measurement. The temporal and spatial differences of velocities in glaciers are good subjects for this type of study.

Velocity relations at depth: Little is known about the distribution of velocity with depth in glaciers, although such information is even more essential to an understanding of glacier flow than surface data. Considerable information on stress–strain conditions at depth, and on the physical properties and behaviour of ice under confining pressures, as they occur under natural conditions, can be gained from the vertical velocity profile in a glacier.

Data on velocities at depth are scant because they are difficult to obtain, but their value justifies the effort. A bare beginning has been made, and more data should be gathered from ice streams on slopes and ice sheets on flats. Those interested in this type of investigation can learn of procedures previously used from the following references: Gerrard, Perutz, and Roch (1952) and Sharp (1953).

Structures in glaciers

Glaciology offers many problems for study, but if an attempt were made to select a few of basic importance, the subject of glacier flow would certainly be among them. Attacks on this problem can be made from various directions and should include both field and laboratory investigations. One avenue of field approach is through study of structures within glaciers. Since most of

these structures have been created by or because of flowage, knowledge of them and their origin is bound to promote understanding of the mode and mechanism of glacier flow.

Planar structures: Crevasses and faults are surface features, to be sure, but they are the product of stresses generated in the crustal ice by movements deeper within the glacier. Field studies of crevasses have not kept pace with theoretical analyses of the stresses leading to their formation (Lagally, 1929; Nye, 1952, pp. 89–91). Brief field inspection shows that crevasses are more varied and complex than might be supposed. Many different types can be recognized, and each type must have a particular meaning with respect to stress conditions in the glacier. Crevasses need the attention of someone well versed in solid state physics and engineering principles dealing with stress, strain, and the behaviour of brittle materials. Faults should also be studied, for they are just as significant, and perhaps easier to interpret.

A thorough investigation of foliation in glacier ice would likewise be desirable. A satisfactory explanation of its origin, and an understanding of the attitude and structure of foliation planes in various parts of the glacier are lacking. Most investigators regard foliation as a secondary structure imposed on the ice by flowage, but a few look upon it as wholly or in part a relic of sedimentary layering inherited from the firn. However, even among those regarding foliation as secondary, the mode of origin is a subject of some debate. This is a matter intimately related to the mechanics of glacier flow, and an understanding of either is likely to be promoted by advances in the other. A satisfactory explanation is also lacking for the fact that the spoon-shaped structure of foliation planes, observed near the terminus of a simple valley glacier, does not extend any distance up the glacier, at least on the surface.

In recent years geologists have made considerable progress in understanding the form and emplacement of relatively homogeneous igneous bodies through careful mapping of all structures displayed therein. Similar investigations of glaciers might prove fruitful if all crevasses, faults, foliation planes, debris layers, sedimentary structures, lineation (if any can be recognized) and related features were mapped. This would be difficult to do because structures in glaciers are usually so profuse and locally so complex that detailed mapping leads more to frustration and confusion than to clarification and understanding. Anyone undertaking such a study should select the smallest, simplest glacier available as an initial subject.

Rhythmic banding (ogives) in steep valley glaciers deserves further investigation because it in turn can lead to an understanding of the mechanics and behaviour of these ice streams (Leighton, 1951). The interrelation of individual ice streams in compound valley glaciers, and the origin of the complexly deformed debris layers displayed by many ice masses present unsolved problems worthy of study.

Crystal fabrics: Investigations of crystal fabrics in glaciers are undergoing the same history as the earlier studies of fabrics in rocks. Strong orientation patterns have been demonstrated, but no satisfactory explanation

for them has yet been evolved. This comes about in large part because knowledge of the behaviour of polycrystalline aggregates of ice under stress is so incomplete. Laboratory investigations are clearly called for, and a beginning is being made in this direction, particularly by J. W. Glen in England, and by D. T. Griggs and G. P. Rigsby in the United States.

It is entirely possible that the strong crystallographic orientations demonstrated in ice at the glacier's surface (Rigsby, 1951, 1953) are the product of an ordered recrystallization proceeding from an orientation earlier established by flowage at depth. A study of ice samples obtained from considerable depth by coring would be helpful in evaluating this hypothesis, if the relaxation rate is not too rapid and if the specimen is not too greatly disturbed by the coring procedure. Core drilling in glaciers has so far been too shallow for such purposes (Miller, 1953, p. 14), but this matter should be pursued further.

Much remains to be done with field studies of crystal fabrics, and a recent suggestion that shear planes of several different orientations in the glacier are involved merits further investigation (Schwarzacher and Untersteiner, 1953, pp. 121–4). However, the greater need at the moment is for controlled laboratory experimentation to establish the principles by which preferred orientations are developed in aggregates of ice crystals.

Phase relations in glacier ice

In 1950 H. Bader made an exploratory study of relations between the liquid, vapour, and solid phases of water in glaciers with respect to the conditions of temperature and pressure to which the ice had been subjected. This work was largely preliminary in nature, and the results obtained were different from those expected. Nonetheless, it appears that much can be learned concerning the properties and behaviour of ice at depth within a glacier from investigations of phase relations. Some of this work can best be done in the field, as the laboratory cannot reproduce wholly satisfactorily the conditions to which the ice in glaciers is subjected.

Oxygen-isotope studies in snow, firn, and glacier ice

Pioneer investigations of oxygen-isotope ratios (O^{18}/O^{16}) in waters of various origins reveal that water in glaciers is exceptionally light, that is low in O^{18} (Epstein and Mayeda, 1953). Furthermore, preliminary studies show sizeable differences in the O^{18}/O^{16} ratio within a single glacier. Data are still too scanty to demonstrate any consistent trends in the oxygen-isotope ratios in glaciers or to relate them to other factors, but these differences may well reflect environmental conditions at the point of origin of the ice, or they may be influenced by something within the subsequent history of the ice such as age, amount of flow and recrystallization, and temperature regime. This type of investigation is in its earliest stages, but it looks promising. Close cooperation between the geochemist and the field glaciologist will be required to produce results.

Micrometeorology and the regime of glaciers

Micrometeorology has been studied for some time with vigour and profit in Scandinavian areas (Wallén, 1948), but it has been largely neglected in North America, save for some work currently underway (Hubley, 1953). Glaciers are frequently referred to as "historians of weather", but weather records from glaciers cannot be interpreted without an understanding of how they respond to the various meteorological factors. Furthermore, the relative influence of the several meteorological elements involved displays such gross variation, depending upon environment, that detailed studies on many different glaciers in many different areas will be required before an evaluation of the basic relations will be possible.

A means of checking the reliability of micrometeorological studies is available if a correspondingly accurate determination of the ablation of firn and snow can be made. Measurements of ablation to date have been too crude and inaccurate to provide reliable values for balancing the ablation equation. It is not feasible to go into details here concerning the difficulty of making an accurate measure of ablation in firn or snow (Hubley, 1953, p. 18). It is a difficult matter, but one well worth considerable study and effort.

Micrometeorological studies on glaciers have significance outside the field of glaciology. The proper evaluation and understanding of climatic changes recorded by present and past glacier behaviours have a bearing on all activities of mankind affected by the climatic environment. The science of meteorology should also benefit, as a glacier surface furnishes an ideal subject for studies of heat exchange at the earth's surface.

Closely allied with the subject of glacier response to climatic change is the synchronism or non-synchronism of glacier behaviours in widely separated regions. When one deals with ancient fluctuations of glaciers the techniques of glacial stratigraphy and geobotany come into play, but even these ancient fluctuations should be interpreted on the basis of sound glaciological and micrometeorological principles. Eventually, Carbon-14 dating may be helpful in establishing the more ancient relations, provided the method can be properly refined and applied to the problem. A demonstration of closely synchronous glaciations in opposite hemispheres, with some degree of antiquity, would have major significance with respect to theories bearing on causes of glaciation.

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PERMAFROST RESEARCH

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"Permafrost" is a term now widely used to describe perennially frozen ground, a phenomenon which is peculiar to cold regions and at once of unusual scientific interest and of great practical significance. "Pergelisol" has been suggested (Bryan, 1946) as a more accurate name for this ground condition and "cryology" for its study, but the problems introduced into the development of arctic and subarctic areas by perennially frozen ground are becoming well known, and popular usage already appears to have eliminated the possibility of these desirable semantic clarifications. Some of the specialized problems concerned with permafrost are discussed in the papers on geophysical exploration, geology, agriculture, and meteorology in this volume; here the subject will be considered as a whole and the research which has been started and the challenging problems which face those engaged in this branch of scientific enquiry will be outlined.

It is not surprising to find that a large proportion of the surface layers of the northern land mass of the world is always at a temperature below freezing point. It is not generally appreciated, however, that about one-half of the area of Canada (Jenness, 1949) and as much as one-fifth of the land area of the world is perennially frozen near its surface (Muller, 1945). Some of this vast area consists of exposures of solid rock, the properties of which are not significantly changed by freezing or thawing. But when soils or coarsely crystalline rocks form the surface of the ground, especially if water is present in them, their character may be markedly affected by changes of temperature above or below freezing point. The term "permafrost" should correctly be used to describe all parts of the earth's surface which are consistently below a temperature of 0°C, and not merely perennially frozen soil.

Permafrost is no new phenomenon. It is at least contemporaneous with the present cycle of climatic conditions in the Arctic. It was recognized by Alexander Mackenzie and by other early travellers in the north but it is only in comparatively recent years that it has become a problem. As long as water in the summer and snow in the winter provided necessary transportation routes, and with buildings of simple design, the summer thawing out of permafrost was unimportant. When, however, frozen ground had to be cleared, first for road construction and then for the building of airfields, and with the advent of heated basements for buildings, the peculiar properties of permafrost made themselves very evident, especially to engineers. At the same time, the

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rapid extension of scientific work in the north has also automatically directed the attention of geologists in particular to a ground phenomenon which had for long been neglected.

Within the last decade, therefore, active programs of permafrost research have been started by United States authorities in Alaska, and even more recently similar work has been commenced in Canada. Individual studies had naturally been carried out previously, but an integrated approach to this problem is yet another development that resulted from the Second World War, for it was the building of the Alaska Highway and the construction of northern airfields which showed vividly how little was known about this peculiar feature of northern regions.

Detailed investigations were made along the Alaska Highway by United States authorities (Eager and Pryor, 1945). The U.S. Army Corps of Engineers subsequently established (under their St. Paul District Office) a field research station near Fairbanks (*Civil Engineering*, 1947), which is now under the direction of the Arctic Construction and Frost Effects Laboratory of the U.S. Army Corps of Engineers at Boston. This station has already carried out notable experimental work. It has since been joined in its efforts by the Snow, Ice and Permafrost Research Establishment of the U.S. Army Corps of Engineers, located at Wilmette, Illinois, whose mission is to perform research for and to coordinate the research program of the U.S. Department of Defense. The U.S. Geological Survey has had members of its staff engaged upon detailed field studies of permafrost, some of this work being linked with that of the U.S. Naval Petroleum Reserve at Point Barrow (Black, 1951). The programs of these several organizations in Alaska constitute the outstanding contribution to permafrost research in North America; although much of the work has been classified in character, enough records have been published to indicate the great value of the results obtained.

Development along the Mackenzie River Valley, the building of the Hudson Bay Railway, and the steady northern expansion of mining activity in the Dominion have combined to demonstrate to Canadians some of the problems associated with permafrost, but the knowledge and experience thus gained have not been widely circulated. The development of the small oil refinery at Norman Wells by Imperial Oil Limited, and the associated wartime Canol project, resulted in rather more detailed investigations (Hemstock, 1952) of this interesting area.

It was therefore not surprising when, after a survey of permafrost conditions in northern Canada, the Division of Building Research of the National Research Council of Canada selected Norman Wells as the site of its Northern Research Station. This was established in 1952 in cooperation with Imperial Oil Limited. It is intended that this station will be both a base for field and laboratory studies of permafrost, and a centre of information in connection with the special problems of building in the north of Canada. Work at Norman Wells is being started in close association with the United States organizations already noted so that duplication of effort will be obviated and integration of work ensured (Pihlainen, 1951).

All the problems connected with permafrost are determined by the local pattern of ground temperature. Temperatures in the ground are determined by the transfer of heat to the surface from the centre of the earth, representing a heat gain to the covering layer, and by the heat losses and heat gains at the surface, which are determined by the thermal environment above ground. Two distinct parts can be recognized in the heat exchange between surface and atmosphere, the conduction–convection heat exchange with the air and a radiant heat exchange with the sky. The former may at any given time represent a heat gain or a heat loss; the latter involves a large heat gain to the earth when the sun is shining, and a much smaller radiation exchange when the sun is not shining, which may be either a gain or a loss. Day-to-night variations in both air temperature and solar radiation may therefore cause a daily fluctuation in ground temperature, marked at the surface but extending only a few inches in depth because of the heat storage capacity of the earth. The yearly cycle is similar, but with the longer period the depth of influence may extend as much as 20 feet below the surface. There is also the possibility that a still longer cycle, involving geologic time intervals and therefore effective over a much greater depth, may also be involved. Other factors such as wind, snow cover, rainfall, evaporation, and vegetation cover may introduce variations in the thermal pattern, in addition to those inherent in air temperature and sunshine and in the physical properties of the ground (Legget and Peckover, 1949).

In southern Canada, it is usual for the ground to freeze in mid-winter although only to a relatively shallow depth. Because of the time-lag in temperature changes beneath the surface, the frost layer may be correspondingly lowered as the year advances, but, even in extreme cases, it will have disappeared by mid-summer. The annual mean temperature in this upper crust, about which the annual variations take place, appears usually to be very close to the mean annual local air temperature. The mean annual temperature of local ground water will be similar.

In areas where permafrost is encountered the local annual mean soil temperature is below freezing, but with the coming of summer the temperature of the upper crust will be raised above freezing point. This thawing will be evident only in those soils which contain water (clays and silts and some soil mixtures, sands, and gravels), and their consistency may change from being solid and rock-like to being wet and sloppy. This part of the soil which thaws out is called the "active layer". Its depth may vary locally from year to year but, under natural conditions, the variation will be small. The muskeg which is so prevalent over permafrost acts as an excellent insulating medium and tends to keep the active layer shallow.

When the muskeg, or any other natural cover, is removed, as in the clearing operations for road building, then the normal thermal pattern is lowered, frozen soil which has not previously been thawed will be so affected, and the problems of the engineer begin especially if, as is so frequently the case, the newly thawed-out soil has a high moisture content. If artificial heat, for instance from a heated basement, is applied to such frozen ground, then

Fig. 1. Thawing of frozen soil following clearing for road construction; the soil was a fine silt with such a high moisture content that it slumped and flowed as it thawed, once the vegetation cover was removed.

the problems created may extend throughout the year instead of being confined to the warm months of summer.

The problems demanding research in connection with permafrost almost suggest themselves from this brief outline. First, and perhaps most obvious, is the need for accurate knowledge of the distribution of permafrost so that those who have to plan operations in the north may know with certainty if they are going to work in a permafrost area, irrespective of the time of year when they have to make their site studies. This knowledge is essential for engineering operations, but it is also of importance for agriculture. Such regional survey research work is well advanced in Alaska, and investigation of the southern limit of permafrost has now been started on a detailed scale in Canada by the Division of Building Research of the National Research Council. The correlation of meteorological statistical studies with permafrost distribution is another major research task in which only a start has been made, and which could be attempted despite the scarcity of long-term climatic data for the north.

These approaches are regional in character and yet the practical problems which permafrost creates are usually quite local. Further advances must therefore be made in techniques of detecting permafrost with certainty and yet with a minimum expenditure of time and money. Aerial photo interpretation gives promise of aiding this work considerably (Woods *et al.*, 1948), both for detailed site surveys and for regional surveys, but much more work

is required in developing such aids as specific interpretation keys. Geophysical exploration methods have been used with considerable success in Alaska,[1] and much research is still being done along these lines.

The need for such detailed local information results from the fact that there is no regularity in the southern limit of permafrost, despite the smooth line which may be indicated on small-scale maps. Moreover, there may often be a conflict of local opinions as to whether permafrost is or is not present at a particular site. This may be due, in cases where the local soil is dry sand and gravel, to the absence of water, the dry material failing to reveal its frozen state through visual inspection alone. Since these soil conditions appear almost ideal for building sites, the possible change in ground conditions when vegetation cover is removed and surface drainage can enter such dry frozen ground may be serious. Little is known of building on this type of site, but much could be learned from a research study.

Similar detailed local studies must be made of the performance of roads, airports, and ordinary buildings which have to be built on permafrost, but this type of investigation is perhaps the most obvious of all desirable permafrost research so that it need be no more than mentioned. What is not so obvious is the research necessary into the effect upon permafrost of unusually large structures, especially those which expose much metal, such as steel towers, and which therefore act as collectors for solar radiation. An interesting theoretical approach to this problem has been made by Nees (1952).

No detailed investigations of engineering problems can proceed very far without the necessity for accurate data (or assumptions, in the absence of data) on the physical and mechanical properties of frozen soils of varied types. Some work has been done, but so far this has only been enough to show the need for extensive laboratory and field research into the many complex aspects of this matter (Hardy and D'Appolonia, 1946). Fortunately, such investigations should serve a dual purpose as much should be learned at the same time about the mineralogy of these soils and so about their geological origin and history. Of even greater interest, however, will be the search for an explanation as to how the soil became frozen. Many samples of soils in permafrost, for example, have a phenomenally high water content and a structure rarely encountered in normal soils today.

This, in turn, leads to the greatest question of all in relation to permafrost. Is it merely the cumulative result of successive winter seasons or is it a relic of the last ice age, or is it partly recent and partly relic? There are some who have already formed their own conclusions on this question. There are others (of whom the writer is one) who still have open minds on the subject and who will, therefore, welcome all research work which may throw some light on this unusually significant matter.

It is probable that all approaches to this question will have to be very long-term in character. Fortunately a start has been made at one approach by the installation of sensitive temperature-measuring devices in at least two very deep holes in the Arctic. One of these is a United States venture at

[1] *See* paper by H. R. Joesting in this volume.

Point Barrow, Alaska (MacCarthy, 1952) and the other Canadian at Resolute Bay, Cornwallis Island (Thomson and Bremner, 1952). Results so far obtained show that the ground is below 0°C at both locations to a depth considerably in excess of 1,000 feet. If arrangements can be assured for the maintenance of accurate temperature records over a long term of years from these and many similar holes which may be instrumented, the puzzle of the character of permafrost may one day be solved.

Finally, reference must be made to Russian work and to the striking similarity that must exist between the permafrost problems of North America and those of the U.S.S.R. Early Russian studies were pioneer steps in this field of applied scientific research, and their publications of the 'thirties show clearly how far advanced permafrost studies in the U.S.S.R. were even at that time. It is known that this early Russian work has been continued and extended and a Permafrost Research Institute established, but few recent Soviet publications on permafrost have become available in North America. It is greatly to be hoped that in the future information on this strictly factual and scientific subject will be freely exchanged between the U.S.S.R. and North America.

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GEOPHYSICAL RESEARCH IN ALASKA

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SEVERAL fields of geophysical research depend for basic data upon observations of geodesy, which treats of the size and the shape of the earth. The following account describes the status of the geodetic network, of observations in the fields of gravity, geomagnetism, radio propagation, and seismology in Alaska, and suggests some problems of further study and research.

Geodesy

Observations over first order arcs of triangulation are adjusted by use of conditioning equations to provide a horizontal datum plane of reference. The adjustment of lines of precise level furnishes fixed elevations above the datum of sea level. The latter is determined by tidal observation at the sea coast over a period of years. Astronomical and gravity observations complete the data necessary to coordinate the network of meridians and parallels and points of precise elevations which are necessary for the delineation of surface characteristics and the determination of the geoid. In both the United States and Canada geodetic surveys are a government responsibility.

In Alaska the Coast and Geodetic Survey has made triangulation surveys along the entire coastal area. A continuous scheme of triangulation extends from the British Columbia–Alaska boundary through southeastern and southwestern Alaska, to the western extremity of the Aleutian Islands; by connection with the Alaska Peninsula, along the shoreline and on the islands of the Bering Sea to Bering Strait, the Arctic Ocean, and Point Barrow; thence along the northern shore of Alaska to the 141st meridian, where a junction is made with the survey of the International Boundary Commission. The latter triangulation completes the geodetic network around the periphery of Alaska. A connection has been made with the geodetic network of Canada in southeastern Alaska and on the Alaska Highway. In the interior, connecting loops exist over the areas adjacent to the Alaska Railroad, Richardson Highway, Glenn Highway, Tok Cutoff, Steese Highway, Yukon River from Tanana to St. Michael, Holitna River, Kuskokwim River, and east of Kotzebue Sound. Recently, arcs of triangulation have been extended from Fairbanks to Umiat, west to the Bering Sea shores and north to the arctic coast at the mouth of the Colville River; from Tanana to the Porcupine River, thence upstream to the

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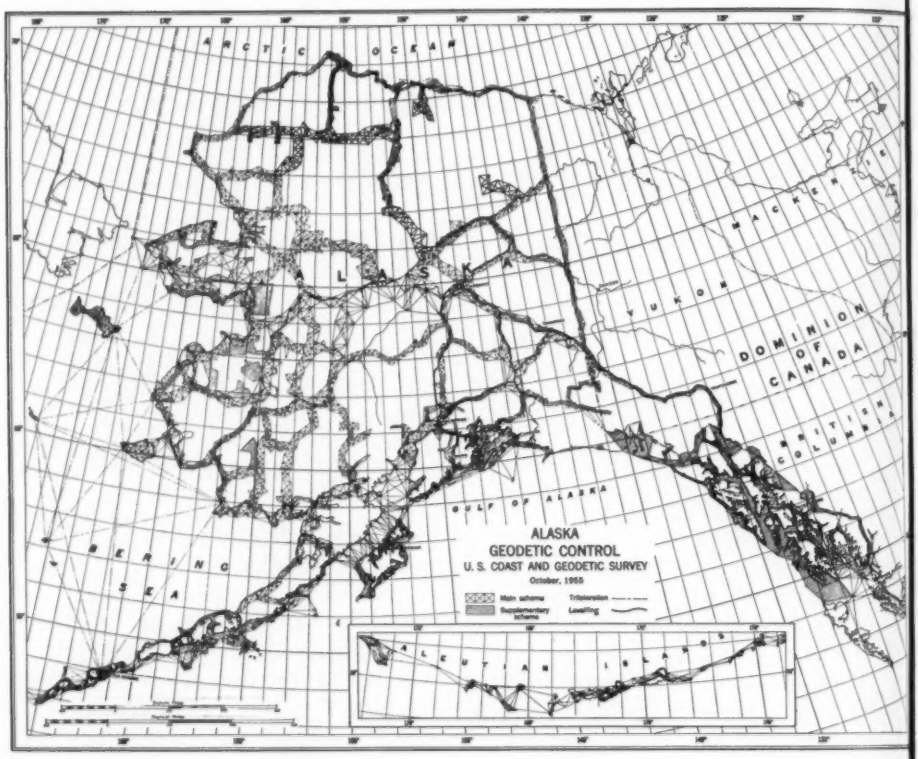

Fig. 1. Geodetic control in Alaska.

Alaska–Yukon Boundary. In addition to the main geodetic scheme, the Geological Survey and the Corps of Engineers have carried out triangulation projects for the preparation of topographical maps.

The elevations of established bench marks above mean sea level have been determined by lines of precise levels on the Alaska Highway from Whitehorse to Fairbanks, on the Richardson Highway from Fairbanks to Valdez and Chitina, on the Glenn Highway and the Tok Cutoff, and on the Steese Highway from Fairbanks to Circle, also from Haines over the Haines Cutoff. The long-range program contemplates levelling on the new highway from Paxson on the Richardson Highway to Cantwell on the Alaska Railroad; from Fairbanks to Livengood, and from Livengood to Eureka, thence to Manley Hotsprings, and downstream on the Yukon River to Kaltag, and thence to Unalakleet and St. Michael on the Bering Sea coast, where connections will be made to tidal bench marks.

The determination of the value of gravity at selected intervals for studies of the figure of the earth is one important phase of geodetic operations. In Alaska the immediate purpose of the gravimetric program of the Coast and

Geodetic Survey is first to establish a system of gravity bases, and then a regional pattern of gravity stations determined with the gravimeter. The plan is to obtain sufficient gravity detail in one or more areas that gravimetric deflections of the vertical can be determined. These deflections, combined with astronomic-geodetic information referred to the North American 1927 datum, should produce valuable data for future determinations of the figure of the earth.

Another phase of this work is the basic coverage of gravity determinations for use in geophysical prospecting. Normally the value of gravity varies according to latitude and elevation. Any anomalous value indicates divergences which may probably be attributed to changes in the consistency of the earth's crust. Investigation of areas where anomalies occur may lead to the discovery of metallic ores or oil-bearing strata.

Gravity bases were recently determined by pendulum apparatus at Point Barrow, Umiat, Fairbanks, Anchorage, and Kodiak. Seventeen pendulum stations have been established between 1897 and 1952, and cover a latitude range from the 58th parallel to Point Barrow. Combined with the gravity pendulum project along the Alaska Highway the necessary basic control will be provided for more extensive gravimetric coverage. The ultimate goal is an area-breakdown of gravity determinations using gravimeters calibrated with reference to the basic gravity pendulum stations.

Future work

Considering the vast unmapped areas of arctic North America, it is essential that the programs initiated by the United States and Canada continue and, if possible, be accelerated in the interest of geophysical research. In Alaska, the long-range program calls for the extension of these surveys in the large area between the Yukon River and the Arctic Ocean, and for a gradual breakdown by means of closer spacing of arcs of triangulation to form a continuous geodetic network with all survey monuments interrelated. The program for shoran photogrammetry will extend knowledge of basic features of this area for topographical maps, for geological surveys, and for further detailed research.

Among the many problems in the Arctic of concern to the geodesist, the following may be listed:

1. Stability of survey marks. What is the best type of monument to set in various types of soil in the Arctic so as to ensure that the survey point will be stable in position both horizontally and vertically? There is already a limited amount of information available, but research with a definite program over a period of years is needed.

2. Vertical land movements. The relationship of mean sea level to surrounding land areas at the head of Lynn Canal has changed over a period of years. Are similar changes occurring at other places in the Arctic and Subarctic? Is the land rising, or the sea falling?

3. Horizontal land movements. In the regions of pronounced seismic activity in Alaska are movements occurring similar to those in California?

Seismologists and geologists can perhaps tell the geodesist of regions susceptible to such movements so that a program of visual observations over a period of years may be initiated.

4. Heights of mountains. Elevations of Mount McKinley recently determined show an increase over earlier determinations. Is this increase due to greater deposition of snow on the peak, to greater precision in the measurements, or is it a real increase?

Geomagnetism

Geomagnetic data in Alaska have been gathered for many years by the Coast and Geodetic Survey. The work began with scattered observations by field parties in those areas most accessible to water routes, and by the establishment of the magnetic observatory at Sitka at the turn of the century. The present activities include the operation of magnetic observatories at Sitka, College, and Point Barrow; a network of repeat stations where observations are made at intervals of five years; broad regional surveys by airborne instruments; and steady accumulation of observations obtained by field parties primarily concerned with other phases of the Survey's activities.

Scientifically, the most important part of the magnetic work is that carried out at the laboratories, where highly trained observers maintain virtually unbroken recordings of changes in direction and intensity of the earth's magnetic field, and carry out frequent observations with absolute instruments. The repeat data are of importance in filling in the patterns of secular change; these stations are usually placed at sites convenient to air transport. The airborne surveys at high levels provide vital facts on the general patterns of distribution of the permanent field over vast interior and offshore areas, which cannot be adequately surveyed by older methods except at tremendous cost. Incidental magnetic data accruing from other survey field operations contribute to knowledge of local magnetic conditions in coastal waters where frequent occurrence of magnetic irregularity offers a potential menace to safety at sea.

One reason for special interest in Alaskan magnetic work lies in the fact that the Territory is nearly bisected by the auroral zone, and is ideally situated for a chain of magnetic observatories extending north and south of that zone. Valuable data on the pattern of magnetic storms and associated phenomena are being provided by the Sitka, College, and Point Barrow magnetic observatories.

Future work

It is clear that the relations of geomagnetic work to navigation, land surveying, radio propagation work, and geological investigations are all of such a nature as to stimulate and justify a sustained and expanded program in this vital field of science.

The following are some of the problems on which future work is needed:

1. The riddle of the elongated pattern of the permanent field northwest of the known magnetic pole.

2. The behaviour of the auroral zone, especially during times of enhanced magnetic activity.

3. The development of procedures for forecasting the various kinds of solar and terrestrial activity that pertain to magnetism and to the use of radio facilities.

4. Increased understanding of daily magnetic variations, particularly with a view to eliminating the effects of various transient fluctuations from magnetic survey data, so that they may be of maximum benefit in geophysical and technological applications.

Some of these problems are currently being studied at the Geophysical Institute of the University of Alaska, and others at various establishments in the world centres of scientific study. There is need for closer spacing of repeat stations to delineate more accurately the location of isomagnetic lines in the northern area and to give basic data for comparison with airborne magnetic surveys and geophysical prospecting investigations.

Ionosphere studies

A study of radio wave propagation in the Arctic is part of an extensive research program of the Central Radio Propagation Laboratory of the National Bureau of Standards. The laboratory either operates, or has supplied equipment for the operation of eight arctic field stations to make regular soundings of the ionosphere at vertical incidence. Three of these are in Alaska (Point Barrow, College, and Anchorage), two are in Canada (Resolute Bay and Baker Lake), two are in Greenland (Godhavn and Narsarssuaq), and one is in Iceland (Rekjavik). The laboratory receives the data from these stations and is also provided with tabulations of hourly measurements made at each of nine other foreign arctic stations.

The observations at these stations give a measure of the electron density in the ionosphere. The variations of electron density with height, and the variations with time of day, season, and solar activity are of great theoretical interest and also of practical importance in studies aimed at improving radio communication in the Arctic. At College regular auroral observations are made, which include measurements of height and brightness. The radio data, when combined with these observations, not only add to the understanding of the relatively modern problems of radio wave propagation but should also aid in the solution of the ancient riddle of the Aurora Borealis.

The importance of these arctic studies by the National Bureau of Standards cannot be over-emphasized. Since radio gives the only possible means of communication over much of the vast area, any improvement in radio communication is extremely valuable. In addition, theoretical investigations of the arctic upper atmosphere may lead eventually to a better understanding of the physical world.

Seismology

Alaska is in general an area of only moderate seismological activity, but with important exceptions. The Aleutian Islands, the Alaska Peninsula, the

southern half of central Alaska, and southeastern Alaska are all marked by major activity. The areas are part of the major tectonic formation known as the circum-Pacific earthquake belt, the most extensive of all such belts. It is characterized everywhere by young and growing mountains on land and by deep parallel trench formations off the coasts. In 1899 at Yakutat, near the eastern end of this belt, one of the greatest known earthquakes occurred, which shifted the shore rocks vertically by as much as 47 feet. In the trench southeast of Unimak Pass, in 1946, a submarine quake caused the sea bottom to rise initiating a seismic wave that destroyed the lighthouse at Scotch Cap with the loss of several lives, and then travelled across the deep Pacific Ocean to kill 173 people and destroy $25 million worth of shore property at Hawaii.

Seismographs are operated at the Sitka and College geomagnetic observatories of the Coast and Geodetic Survey in Alaska. These stations and others outside Alaska provide the data needed to detect and locate the more important earthquakes originating in Alaska, to outline the various zones of seismic activity in the region, and to ascertain the degree of earthquake hazard in each. This information is of special value to engineers designing important structures, and to insurance companies needing statistical information on which to base earthquake insurance rates. Seismological techniques are also of value to geophysical prospectors.

Future work

Because the transmission and changing velocities of different types of seismic waves over various paths through the earth's interior can be calculated from seismographical data, significant deductions can be made regarding the structural and physical state of the interior of the earth. Additional seismological stations should be located in non-active areas in the north and along the arctic coast for this study.

GEOPHYSICAL EXPLORATION IN ALASKA*

H. R. Joesting†

IN ALL parts of the world, geophysical exploration is concerned with the composition, form, and structure of the crustal rocks, with the search for minerals, mineral fuels, and ground water, and with problems of civil engineering and construction. In Alaska it is also concerned with permafrost, which has a marked modifying effect on the properties and distribution of near-surface materials, especially of unconsolidated deposits. Permafrost can usually be identified and mapped by geophysical methods, and it has therefore become a major field for geophysical investigation in Alaska.

In this paper I have attempted to review geophysical investigations in Alaska of geologic and related problems and to indicate problems worthy of future investigation. The earlier investigations are emphasized because relatively little information on them has been published. Permafrost investigations are also emphasized because of their importance in cold regions. Conversely, the recent extensive petroleum explorations in northern Alaska are treated more briefly than their importance might seem to warrant, because they are generally similar to petroleum explorations in other regions. In some instances it has been necessary to distinguish rather arbitrarily between geologic and geophysical endeavours, which are usually complementary. The paper is not intended to be exhaustive or complete, and discussions of investigations in fields of geophysics not closely related to geology have been omitted.

Permafrost and related problems

The earliest systematic attempts to use geophysical methods in interior Alaska were apparently all made by the U.S. Smelting, Refining, and Mining Company in the Fairbanks district. In 1928 magnetic surveys were carried out under the direction of E. E. Maillot, assisted by J. C. Boswell,[1] to determine their usefulness in tracing buried gold placer channels. The gold occurs on or near bedrock in gravels covered by as much as 200 feet of silt and muck. (Muck is dark-coloured silt, high in organic and water content and is usually frozen). Boswell concluded that the placers investigated did not contain sufficient magnetic black sands to affect a field balance.

*Publication authorized by the Director of the U.S. Geological Survey.

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[1]Boswell, J. C. 1929. "Application of geomagnetics to placer exploration". Unpublished thesis for B.S. in Mining and Geology, University of Alaska.

In 1933 the same company, using electrical resistivity and potential-drop-ratio methods, made systematic efforts to outline areas of permafrost and determine thickness of unconsolidated material over bedrock. On the whole these tests were not successful,[1] possibly because of the complex stratigraphy and permafrost relations of the partly frozen overburden.

In the summer of 1938 experimental seismic refraction surveys were made under the direction of L. D. Leet and H. G. Taylor for the same company. On the basis of this work, Taylor[2] concluded that the schist bedrock underlying the frozen muck and gravel in the Fairbanks district could not be mapped, because seismic velocities in frozen gravel were almost as high as in bedrock. Bedrock under frozen muck usually could not be mapped, because of variations in velocities in both bedrock and overburden, the latter resulting from thawed spots. Difficulty was generally experienced in determining depths to bedrock and to top of gravel in areas of discontinuous permafrost because of complex velocity relationships. In thawed areas it was usually possible to determine thickness of muck and gravel overlying the schist bedrock, though the accuracy was low in areas of deeply weathered bedrock. Considerable information was obtained on velocities of propagation in the formations in the Fairbanks district, and the following figures were recorded:

Light muck	1,000– 1,650 f.p.s.
Thawed muck	1,800– 4,000
Frozen muck	4,250–10,000
Thawed gravel	2,000–10,000
Frozen gravel	13,000–15,250
Bedrock (schist)	7,500–20,000

Light muck is evidently unfrozen, tan-coloured silt of aeolian origin (Tuck, 1940, pp. 1,299–306).

The rather wide variations in these velocities may have resulted in part from the discontinuous nature of permafrost in much of the Fairbanks district, so that measurements in completely frozen or completely thawed material were not always possible. Thus the lower velocity given for frozen muck (4,250 f.p.s.) may actually be for muck that was largely thawed, and the higher velocity for thawed gravel (10,000 f.p.s.) may result from an "island" of permafrost in otherwise thawed material. It is also likely that the higher velocity recorded for bedrock (20,000 f.p.s.) may result in part from irregularities of the surface of bedrock as well as from complex permafrost conditions.

In spite of the wide variations, Taylor's figures indicate that the velocities in frozen material are in general higher than in their thawed counterparts. This is substantiated by results obtained later in northern Alaska,[3] where velocities in continuous permafrost range between 8,000 f.p.s. in frozen

[1]Crawford, J. R. and E. E. Maillot. 1954. Personal communications.

[2]Taylor, H. G. 1939. "Report on geophysical work by the seismic method in the placer deposits of the Fairbanks district of Alaska". In files of U.S. Smelting, Refining, and Mining Company.

[3]Unpublished reports of United Geophysical Company to Director of Naval Petroleum and Oil Shale Reserves, 1950.

alluvium and 13,500 f.p.s. in frozen Tertiary sediments. The vertical velocities in northern Alaska were slowest and the velocity increased as the travel path approached the horizontal. Barnes[1] found horizontal velocities in frozen alluvium in the Fairbanks district to be comparatively high—of the order of 7,000 to 13,000 f.p.s. He states that a high seismic velocity is an almost sure indication of frozen ground (alluvium) and can only be misinterpreted as bedrock. He also noted that frozen alluvium is markedly anisotropic to the propagation of seismic waves.

Other experimental work includes the studies made by Matthews[2] in 1937 to test the use of the electrical resistivity method in exploring for gold placers in the Fairbanks district, and the more comprehensive investigation by the Territorial Department of Mines during 1938 to 1940 of magnetic and resistivity methods as aids to prospecting, mining, and geologic investigations in interior Alaska (Joesting, 1941). Magnetic surveys were found to be useful in prospecting for buried gold placers under favourable conditions, that is where moderate to large amounts of magnetic black sands were concentrated with the gold in comparatively shallow pay streaks, and where the effects of the black sands were not masked by bedrock anomalies. *In situ* determinations of resistivities of unconsolidated and consolidated rocks in the Fairbanks, Livengood, and Circle districts showed that in general the resistivities of frozen rocks are considerably higher than of comparable thawed materials and that these differences are sufficient to indicate the extent and approximate thickness of frozen unconsolidated deposits. Determinations of depth to bedrock were possible under favourable circumstances but were generally unsatisfactory in areas of discontinuous permafrost. It was also found that the contrast in resistivities between frozen and thawed unconsolidated deposits could facilitate the search for ground water.

In 1944 a brief study of the application of geophysical methods to permafrost problems was made by the U.S. Bureau of Mines and the Corps of Engineers, U.S. Army. Shallow resistivity surveys were made at Northway on the upper Tanana River, at Wolf Creek in the Fairbanks district, and at Galena on the Yukon River; and one seismic refraction station was occupied at Northway. On the basis of these surveys Swartz and Shepard[3] concluded that the top of the permafrost can usually be determined by both resistivity and seismic methods, and that areas of thawed and frozen ground can likewise be mapped by both methods. They also concluded tentatively that the bottom of the permafrost can be determined by resistivity, but not by seismic refraction because of unfavourable velocity ratios, and that ice lenses could be indicated by resistivity.

[1]Barnes, David F. 1954. "Preliminary report on tests of application of geophysical methods to arctic ground-water problems". Unpublished report in files of U.S. Geological Survey.

[2]Matthews, Ted C. 1938. "Application of geo-resistivity to placer exploration". Unpublished thesis for Batchelor of Mining Engineering, University of Alaska.

[3]Swartz, J. H. and E. R. Shepard. 1946. "Report on a preliminary investigation of the possible application of geophysical methods to studies of permafrost problems in Alaska". Unpublished report in files of U.S. Geological Survey.

More extensive experimental resistivity surveys were made in the Fairbanks district in 1948 by the U.S. Geological Survey under the direction of J. H. Swartz. This work substantiated earlier conclusions concerning the use of resistivity in permafrost areas, and the data are being incorporated in a report in preparation. In 1952 the Survey made an evaluation of electrical and seismic methods in the search for ground water in permafrost areas at the request of the Engineer Research and Development Laboratory, Corps of Engineers.[1] Following recommendations in this report, further surveys were made during the summer and fall of 1952. The geophysical work was coordinated with physiographic and ground-water studies and with a limited amount of drilling.

During the summer of 1953 experimental surveys were made by the U.S. Air Force Cambridge Research Center to determine the thickness of permafrost by measuring the frequency dispersion of flexural waves propagated through the permafrost layer. These experiments were made in continuous permafrost in the Farmers Loop area near Fairbanks. According to Hansen[2] records of flexural waves were obtained at distances of 3,000 feet to several miles using large charges placed in the permafrost. The method is based on one used by Press *et al.* (1951) to measure the thickness of sea ice.

Seismic reflection and gravity surveys were made in 1951 by Allen and Smith (1953) on the Malaspina Glacier, northwest of Yakutat Bay, to determine ice thickness and configuration of the subglacial floor. The information was obtained to aid in the study of structural relationships and flow within the glacier. Seismic refraction and gravity profiles were also run in 1952 on the Juneau Ice Field in southeast Alaska in connection with glaciological studies and to determine ice thickness (Miller, 1953a).

Geothermal investigations

In 1949 long-term geothermal studies were initiated in northern Alaska by the U.S. Geological Survey with the support of the Office of Naval Research and the Bureau of Yards and Docks of the Department of the Navy, and later of the Snow, Ice and Permafrost Research Establishment of the Corps of Engineers. These studies, which are still underway, aim to determine the temperatures and thermal properties of perennially frozen and other sub-surface materials in arctic Alaska and to relate them to the geology. Precise measurements of temperature have been made in both deep and shallow holes, most of them drilled in exploring for oil, and thermal conductivity measurements have been made of near-surface materials. The work has been coordinated with the extensive exploration program of the Office of Naval Petroleum and Oil Shale Reserves; the geothermal studies were in fact made feasible by the exploration program (MacCarthy, 1951, 1952).

[1]MacCarthy, Gerald R. and others. 1952. "Geophysical methods of prospecting for ground water in permafrost regions". Unpublished report in files of U.S. Geological Survey.

[2]Hansen, Roy E. 1954. Personal communication.

Temperature measurements in shallow boreholes have also been taken in the Umiat area of northern Alaska by a group from Boston University and in the Fairbanks district by the U.S. Geological Survey and the Corps of Engineers. Other temperature measurements were made in the boreholes in the Juneau Ice Field in southeastern Alaska in connection with glaciological studies (Miller, 1953b).

Sedimentary geology and oil exploration

During the period 1944 to 1953 extensive geophysical surveys were carried out in Naval Petroleum Reserve No. 4 and in much of the rest of northern Alaska on behalf of the Office of Naval Petroleum and Oil Shale Reserves of the Navy Department. Included were regional gravimetric surveys over much of the reserve, seismic reflection and refraction surveys in selected areas by the United Geophysical Company, aeromagnetic surveys of most of the reserve and the area eastward to Flaxman Island by the U.S. Geological Survey, and smaller-scale gravimetric surveys during 1945 by the Bureau of Yards and Docks. These have been discussed in reports by the United Geophysical Company[1] and Payne and others (1951). Additional reports and technical data are available for public inspection in the offices of the U.S. Geological Survey in Washington and the Inspector, Naval Petroleum Reserve, Fairbanks, Alaska.

These large-scale investigations exceed in magnitude the combined total of geophysical exploration already carried out in the remainder of Alaska. They were coordinated with extensive geologic investigations and by considerable test drilling. They were preceded by geologic and other explorations in northern Alaska, largely by the U.S. Geological Survey, over a period of many years, and conditions favourable to the occurrence of petroleum had been indicated by Smith and Mertie (1930), Smith (1939), and Ebbley and Joesting.[2]

As a result of the combined investigations it has been established that the region north of the Brooks Range is a single asymmetric sedimentary basin with its axis parallel to the range. Its deepest part is apparently within the foothills province of the region and not near the coast of the Arctic Ocean as was previously supposed. This sedimentary basin has been broadly defined, and a band of folding at least 30 to 50 miles wide and extending east more than 250 miles across the central part of the reserve has been outlined. In addition several anticlinal folds were examined in detail by seismic methods, especially along the northern part of the folded zone where exposures are insufficient to permit surface mapping of geologic structure (United Geophysical Company, 1954, *see* footnote 1, below); Gates, 1953; Gryc, Miller, and Payne, 1951).

[1]United Geophysical Company. 1954. "Final report on geophysical exploration of Naval Petroleum Reserve No. 4 and adjoining areas of Alaska, 1945 to 1953". Official report to Director, Naval Petroleum Reserve.

[2]Ebbley, Norman, Jr. and H. R. Joesting. 1943. "Report of investigation of petroleum seepages, Arctic Slope area, Alaska". Unpublished report in files of U.S. Bureau of Mines.

Renewed interest has been shown by private concerns in the oil resources of southern and southwestern Alaska during the past few years. In this connection seismic surveys were carried out on the Kenai Peninsula north of Homer during 1954 in areas where exposures of consolidated rocks are scarce.

In addition, the recent discovery of marine fossils in interior Alaska points up the possibility that other parts of the Territory may also contain oil (Payne, 1953; Péwé, 1954). The fossils were found in basal Quaternary deposits near Fairbanks, at the north edge of the middle Tanana basin. They are believed to have been derived from marine Tertiary rocks deposited in the Yukon–Tanana plateau region and removed during the Pliocene uplift, according to Payne. Payne further points out that under favourable conditions marine Tertiary rocks might be preserved in the middle Tanana basin and also in other basins in Alaska. Such rocks would be potential sources of petroleum, especially if considerable thicknesses are present.

Reconnaissance aeromagnetic surveys were flown by the U.S. Geological Survey in several parts of Alaska during 1954 to gain information on the approximate thickness of sedimentary rocks in the basins and also on regional structural trends and buried intrusive rocks. Among the areas flown over were parts of the Koyukuk geosyncline and of the Bethel, Nushagak River, Cook Inlet, Copper River, Yukon Flats, and Tanana River basins.

Metalliferous lodes

The first use of geophysical methods in prospecting for metalliferous lode deposits in Alaska was probably in 1930, by the Schlumberger Geophysical Company. The work was done at the Fidalgo-Alaska mine, on Prince William Sound south of Valdez. The problem was to find additional deposits of chalcopyrite and pyrite, or to extend known deposits. Spontaneous potential, equipotential, and electrical resistivity methods were used and several conducting zones were outlined that may have been related to deposits of sulfide minerals, but no commercial deposits are known to have been found.

No other geophysical prospecting for lode deposits seems to have been done until the period 1941 to 1943, when the Territorial Department of Mines carried out magnetic surveys for tungsten deposits in the Fairbanks district[1] (Joesting, 1943, p. 22), and for chromite deposits at Claim Point on the Kenai Peninsula.[2] Additional geophysical work in 1952 by the Territorial Department of Mines in the Lost River area of the Seward Peninsula, attempted to locate tin-bearing granite cupolas in limestone by use of magnetic and electrical resistivity methods. Negative results were obtained, partly because

[1]Joesting, H. R. and Eskil Anderson. 1941. "Preliminary report on scheelite deposits in the Fairbanks district, Alaska". Unpublished report available for public inspection at Office of Commissioner of Mines, Juneau, Alaska.

[2]Joesting, H. R. 1943. "Geologic and magnetic survey of chromite deposits, Claim Point, Alaska". Unpublished report available for public inspection at Office of Commissioner of Mines, Juneau, Alaska.

of the disturbing effect of permafrost, and of buildings and mining equipment.[1] Reconnaissance magnetic surveys were flown in the tin-bearing areas of Seward Peninsula in 1954, but attempts to locate granite cupolas were again unsuccessful. In the summer of 1954 an electromagnetic survey was made by private interests of the chalcopyrite and pyrite deposits at Horseshoe Bay on Latouche Island, Prince William Sound. Favourable results were reported (Territorial Dept. of Mines, 1954).

A number of dip-needle and magnetic-declination surveys for magnetic iron deposits were made in southeastern Alaska during the period 1942 to 1944. Records are available of surveys in several localities on Prince of Wales Island: on the Kasaan Peninsula (Erickson, 1948, p. 4), in Jumbo basin (Wright and Fosse, 1946, p. 6; Kennedy, 1953, pp. 36–8), and in the Mt. Andrew area.[2]

Several aeromagnetic surveys have also been made in connection with prospecting for metallic minerals. Among those in southeastern Alaska are a survey by the U.S. Geological Survey of southern Prince of Wales Island to obtain geologic information in an area containing deposits of magnetite and associated copper minerals,[3] and surveys by private interests of parts of the Mansfield Peninsula for nickeliferous deposits and of the Snettisham area for magnetic iron deposits.[4]

A reconnaissance aeromagnetic survey was flown in 1954 by the U.S. Geological Survey in the Snag River area, north of the Nutzotin Mountains, to relate magnetic and geologic features and to determine the magnetic effect of a mineralized zone that had been mapped in the adjoining area in Canada.

Radioactive minerals

Reconnaissance surveys for deposits of radioactive minerals have been made during recent years in many parts of Alaska both on foot, by car, and by aircraft using Geiger and scintillation counters. Most of these investigations have been made by the U.S. Geological Survey; their scope is indicated in publications by Gault *et al.* (1953), Moxham and Nelson (1952), Wedow,[5] and Wedow and others (1953).

Other investigations have been made by the Territorial Department of Mines, and recently there has been increasing activity by prospectors.

[1]Williams, J. A. and R. H. Saunders. 1953. "Geophysical exploration at the Lost River tin deposit, Alaska". Unpublished report available for public inspection at Office of Commissioner of Mines, Juneau, Alaska.

[2]Goddard, E. N., L. A. Warner and Matt Walton. 1944. "The copper-bearing iron deposits of the Mt. Andrew–Mamie area, Alaska". Unpublished report available for inspection in office of U.S. Geological Survey, Washington, D.C.

[3]Henderson, John, and others. 1954. "Aeromagnetic map of the southern part of Prince of Wales Island, Alaska". Open-file map available at offices of U.S. Geological Survey in Washington, D.C., Los Angeles, Menlo Park, San Francisco, and Denver, and in Anchorage, College, and Juneau in Alaska.

[4]Holdsworth, Phil. R. 1954. Personal communication.

[5]Wedow, Helmuth, Jr. 1951. "Adaptation of portable survey meters for airborne reconnaissance with light planes in Alaska". U.S. Geological Survey TEMR 323, released by Technical Information Service, U.S. Atomic Energy Commission, Oak Ridge, Tenn.

Additional airborne surveys were made in 1954 by the U.S. Geological Survey in the following areas: Buckland–Kiwalik, Nixon Fork, Tyonek, Yakataga Beach, and Nutzotin (Snag River).

Volcano research

A program of volcanological research in the Aleutian Islands was prompted by the eruption in June 1945 of Okmok volcano near Fort Glenn on Umnak Island. Geologic and geophysical investigations were started by the U.S. Geological Survey in 1946 at the request of the War Department. The geophysical investigations, which were terminated in 1954, were supported jointly by the Office of Naval Research and the U.S. Geological Survey (Swartz, 1951).

In connection with the geophysical investigations seismographs were set up on Adak and Great Sitkin islands to record earthquakes related to volcanic activity in the Aleutian Islands and tectonic activity in the Aleutian Trench. Measurements of earth tilt and of changes in the earth's magnetic and electrical fields were also made near Great Sitkin volcano.

Problems for future investigation

Except for problems related to permafrost, problems of geophysical exploration in Alaska are generally comparable to those in the western United States and western Canada. As these problems are practically infinite in number and variety, this discussion is restricted to those that appeal to me as interesting and important.

Permafrost

Permafrost—its distribution, physical properties, and origin; its relation to climate, vegetation, and animal life; and its effect on human activities—remains a field for investigation of first importance in northern regions, and one that has been pursued more assiduously in the U.S.S.R. than in Alaska. Geophysical methods, usually in combination with other methods of investigation, provide an effective means of adding to our knowledge of the distribution, physical properties, and origin of permafrost.

The distribution and upper surface of permafrost, for example, can now ordinarily be determined rapidly by electrical resistivity and seismic refraction surveys, supplemented by drilling and temperature measurements. The lower surface of permafrost may also be defined by resistivity, provided the frozen and thawed materials occur in suitably uniform, horizontal layers. Such ideal conditions are seldom found in nature, however, consequently the development of better means of obtaining and interpreting resistivity data in terms of depths to the bottom of permafrost is highly desirable. Seismic refraction methods are usually not suitable for defining the lower surface of permafrost, because unfavourable velocity relationships usually exist between permafrost and the underlying thawed material, especially where the thawed material is unconsolidated. Seismic reflection methods in theory do not have this limitation. Successful tests of shallow reflection

equipment have recently been made by the U.S. Geological Survey (Pakiser and Mabey, 1954; Pakiser, Mabey, and Warrick, 1954) and this equipment may eventually be useful in defining the lower boundaries of permafrost.

Information on the decay or growth of permafrost and of heat flow from the earth can be gained from measurements of thermal conductivities and temperatures. Precise temperature measurements in boreholes could also conceivably be used to give information on climatic changes during the fairly recent past. In this connection Henderson[1] has computed the effect of a temperature increase of 10°C at the surface, assuming that changes as small as 0.005°C per year or 0.05°C per 10 years can be measured (this is about the limit of present-day equipment). Using reasonable values for thermal diffusivity, on which depends the rate of propagation of a thermal wave, it was found that such a wave could not be detected later than 490 years after it started from the surface. The maximum detectable depth of penetration would be about 800 feet after the lapse of 300 years, if the diffusivity were 0.01, and 1,100 feet after 300 years if it were 0.02. The simplifying assumption of a step-function temperature increase doubtless gives values somewhat greater than would be found experimentally. Field laws governing thermal processes in permafrost have been developed by Redozubov (1946).

More quantitative information on the physical properties of perennially frozen materials, their interrelationships, and their dependence on such factors as temperature, porosity, and permeability is required as a basis for an adequate understanding of permafrost. Electrical, elastic, and probably thermal properties are markedly affected by temperature. Ananiân (1945), Dostovalov (1947), and others in the U.S.S.R. have shown that the resistivity and dielectric constant of perennially frozen materials depend on temperature as well as on other factors, but no quantitative investigations along these lines have yet been made in Alaska.

Adaptation or development of geophysical equipment for use in low temperatures is also desirable, especially as winter is the most favourable season for surface travel in many parts of Alaska. Adaptation of electrical resistivity equipment would require, for example, improved means of generating electrical power, of introducing current into the frozen ground, and of measuring current and potentials, and an insulation that would remain flexible. Development of electromagnetic induction equipment would probably also be worthwhile, as it would eliminate many of the practical difficulties of using electrodes in contact with the frozen surface and would permit more rapid mapping of permafrost. Weasel-mounted equipment could doubtless be developed for continuous cross-country traverses during the winter. Inductive methods have apparently been used to a considerable extent by the Russians in permafrost studies (Petrovsky, 1947; Petrovsky and Dostovalov, 1947 a,b) but little information is available on recent results.

Russian investigators have also noted spontaneous electrical currents at the interface between the thawed active layer and the permafrost layer

[1]Henderson, R. G. 1954. Personal communication.

(Kozin, 1936; Enenstein, 1947). Casual observations have failed to corroborate this phenomenon in Alaska. Systematic studies under known conditions would be worthwhile.

Sedimentary basins and oil exploration

If the Copper River region, Tanana River, Yukon Flats, and similar regions in Alaska prove to be basins of marine deposition as well as physiographic basins, they would become of great interest as potential sources of oil, and intensive geologic and geophysical investigations would be warranted. Such investigations would initially be concerned mainly with stratigraphic and structural relationships and would follow the same general pattern as in other parts of the world. It is probable, though, that airborne surveys would be used to a greater extent, at least in the initial stages of exploration, because of difficulties of surface travel.

Effect of earth's crust on terrestrial magnetism and electricity

In connection with the International Geophysical Year of 1957 to 1958, during which simultaneous observations will be made in many parts of the world of geophysical phenomena such as cosmic radiation, the aurora, geomagnetism, and ionospheric activity, it would seem desirable to carry out a series of magnetic and electrical investigations in which the modifying effects of the earth's crustal rocks are taken into account. More specifically, these should be concerned with the effects on the earth's magnetic and electrical fields, especially during periods of magnetic and auroral disturbance, of spatial variations in the magnetic and electrical properties of the crustal rocks due to differences in their structure and composition. These investigations should preferably be made in areas of high auroral activity, such as the Fairbanks district.

A start along these lines was made in Canada by Morley (1953), who measured two simultaneously operated stations, placed initially 130 miles apart and later 87 miles apart, during periods of severe magnetic disturbance. No attempt was made, however, to compare the amplitude of the disturbances with the magnetic susceptibility of the underlying rocks.

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PROBLEMS OF GEOPHYSICS IN THE CANADIAN ARCTIC

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APART from upper atmospheric studies, which are being dealt with in the chapter on meteorology, the main Canadian contributions to geophysics in the Arctic have been made in the fields of terrestrial magnetism, gravity, and seismology. Systematic programs of observation have already been initiated in these three fields, and are likely to be expanded in time. Those observations which have been made up to the present, together with some arctic problems for future study, are considered briefly in this article. Meteors, meteorites, and meteorite craters are also discussed because of their geophysical as well as astronomical implications.

Geomagnetism. By R. G. Madill

Arctic North America, containing the north magnetic pole and much of the auroral zone, offers opportunities for research on the earth's magnetic field at high magnetic latitudes which can only be equalled in the far less accessible Antarctic. It is an area where the magnetic declination, or variation, of the compass changes through 360 degrees, the inclination, or dip, reaches its maximum of 90 degrees, and the horizontal force decreases to zero. It is here that changes in the direction and magnitude of the horizontal field reach their greatest values from hour to hour and year to year. It is here, also, that magnetic disturbances are almost continuous along the auroral zone which expands during severe magnetic storms, and seriously affects the magnetic field far south of the Arctic.

The earliest magnetic observations in extreme northern latitudes were made by scientists and navigators during voyages of discovery, particularly in connection with the search for a Northwest Passage, and the attempts to rescue the Franklin expedition (Kane, 1856, pp. 165–6; Ross, 1835, pp. 549–71; Sabine, 1872, pp. 353–433). Contributions to the study of terrestrial magnetism in arctic Canada were also made by the International Polar Year expeditions of 1882–3 at Fort Rae (Dawson and others, 1886), Kingua Fiord (Giese and others, 1886), and Fort Conger (Greely, 1886), and of 1932–3 at Fort Rae (Stagg, 1934) and Chesterfield Inlet (Davies and Currie, 1939), which studied the daily and annual variations in the earth's magnetic field and the correlation between magnetic storms and aurorae. Important studies of the

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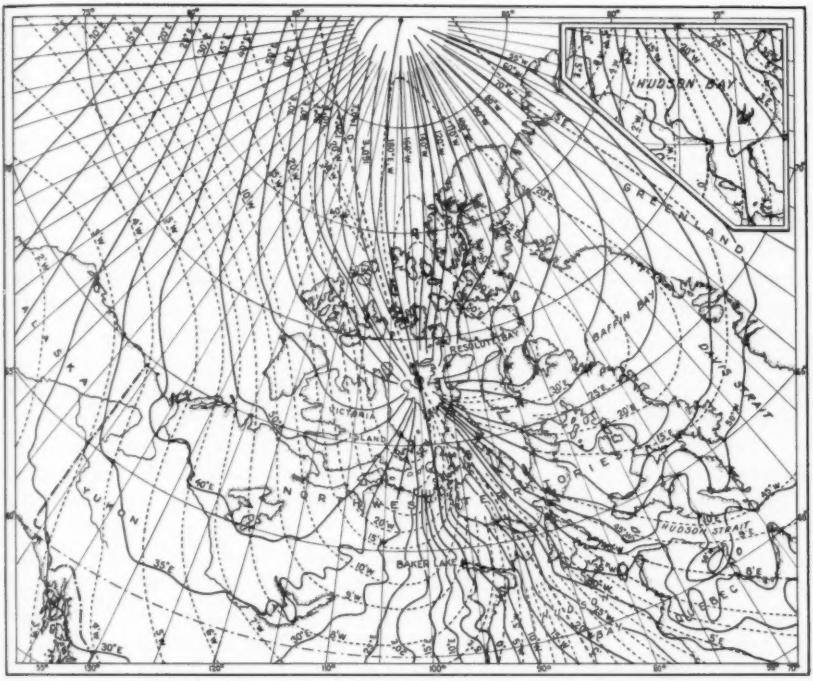

Fig. 1. Lines of equal magnetic declination and annual change in northern Canada.

earth's magnetic field in the vicinity of the north magnetic pole were made by Amundsen in 1903–6 (Steen *et al.*, 1933).

Prior to 1943 regular observations by the Dominion Observatory had extended a network of magnetic stations northwards to include the Yukon and Mackenzie river areas, and such parts of the coasts of Hudson Bay, Hudson Strait, and Baffin, Devon, and Ellesmere islands as could be reached by arctic supply or patrol vessels. Positions at which reliable magnetic observations had been made were very thinly spread over the Arctic, and consequently, magnetic maps did not possess the accuracy required for navigation with any certainty, although they illustrated in a general way the distribution of isogonic lines.

Since 1943 magnetic stations have been established, largely through the aid of the Royal Canadian Air Force, on all main islands of the Arctic Archipelago and the contiguous mainland. The stations north of latitude 60 degrees now number more than 500, and completely surround the north magnetic pole area. Information from these well distributed magnetic stations has made it possible to determine the mean position of the magnetic pole with considerable accuracy, and to construct isomagnetic maps showing lines of equal declination, inclination, and horizontal, vertical, and total force for the entire northern area of Canada (Madill, 1948, 1949). From repeated observations

made at selected magnetic stations, the annual change in the various elements is known with reasonable accuracy. The accompanying declination map, Fig. 1, illustrates present-day knowledge of the earth's magnetic field in the Canadian Arctic.

The value of magnetic results depends not only on the number of stations, and the calibre and training of the observers, but also on the accuracy of equipment. Prior to 1947 no magnetic instruments were available that would give reliable results for both the direction and magnitude in areas of weak horizontal force near the north magnetic pole. However, a new type of magnetometer, designed and constructed by Dominion Observatory personnel, was used for ground survey work in 1947 when the magnetic pole area was surveyed, and proved to be so effective that it has been adopted for magnetic surveys in other parts of Canada as well as in the Arctic. It embodies the saturable core principle, like that used in airborne magnetometers, and operates more rapidly and sensitively than older types of magnetic survey instruments.

The Dominion Observatory has established magnetic observatories at Baker Lake and at Resolute Bay on Cornwallis Island. At both observatories regular measurements of the direction and magnitude of the magnetic field are made and their changes recorded continuously by photographic and electrical variometers. These records have shown that the mean daily range of the magnetic declination at Resolute Bay, which is 120 miles from the magnetic pole, is 7 degrees. The daily variation is much greater in summer than in winter. The maximum range is in June, and amounts to 11 degrees 19 minutes, while the minimum range, in December, is 3 degrees 21 minutes. It is clear that these variations are related to the sun's declination. At Baker Lake, which is 650 miles from the magnetic pole, the daily variation is much smaller, ranging from 4 degrees in June to 40 minutes in December.

The magnetic records from these observatories, apart from their importance in theoretical research, are of immediate practical value. They furnish data which are necessary for interpreting the short- and long-term movements of the north magnetic pole, and are therefore essential for the construction of magnetic declination maps, since all magnetic meridians radiate from the magnetic pole. Moreover, they provide data which are used in evaluating world-wide disturbances in the ionosphere, and they supply essential information required in navigation and in the control of airborne magnetic surveys, which are now being carried out.

Although a satisfactory network of magnetic stations has been established, the magnetic survey of arctic North America has not been completed. A much greater density of stations will be required in the future, not only for general mapping, and further geological studies, but also for use in conjunction with airborne surveys searching for economic minerals. The success of airborne magnetometers in delineating mineralized areas depends directly on eliminating the effects of magnetic disturbances originating on the sun, which cause induced disturbances within the earth's crust. The records from the fixed magnetic observatories are therefore of paramount importance to the geophysical exploration of the Canadian Arctic.

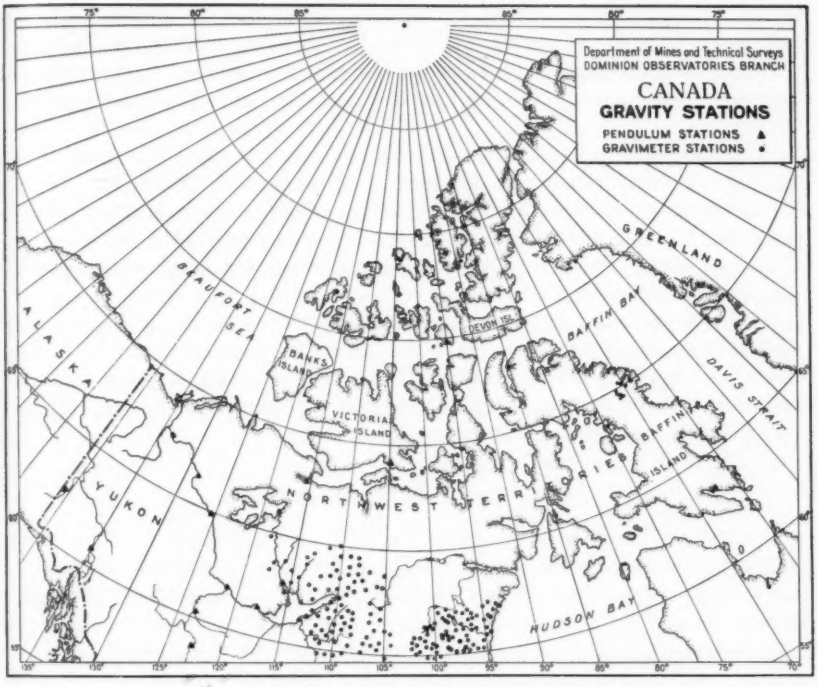

Fig. 2. Gravity stations in northern Canada.

Gravity. By M. J. S. Innes

The earliest pendulum observations in the Canadian Arctic were made by Parry on Melville Island in 1819–20 and at Port Bowen, Baffin Island, in 1824–5 (Parry, 1826), and by G. R. Putnam (1897) of the U.S. Coast and Geodetic Survey, who established two pendulum stations in 1896 in Hudson Strait and Cumberland Sound. The systematic study of gravity in northern Canada was initiated by A. H. Miller (1922) of the Dominion Observatory, who established pendulum stations in 1921 and 1922 at outposts along the Slave and Mackenzie rivers. Another advance was made in 1945 when a Canso aircraft of the Royal Canadian Air Force was employed for transportation, and observations were made at Fort Rae, Cameron Bay, and Cambridge Bay (Innes, 1948). In 1948 two more pendulum stations were established at Frobisher and Resolute Bay by scientists from the University of Toronto, who accompanied one of the icebreakers on a supply mission to the far northern weather stations (Beer, 1950).

It is now possible to measure gravity much more rapidly with modern gravimeters than with the pendulum. Nevertheless, these isolated pendulum determinations are of great value in controlling and calibrating gravimeters.

In fact, it was for this purpose, and for ensuring uniformity within the North American network of gravity stations, that the Dominion Observatory, in cooperation with United States scientists, recently established a line of precise pendulum stations from Mexico City to Fairbanks, which was completed in 1953.

Gravimeters have been used in northern Canada since 1947, to make about 2,000 gravity determinations at intervals of 10 to 20 miles, of which more than 200 lie north of the tree-line. The Dominion Observatory has made plans to continue this program, and to obtain similar gravity coverage throughout the whole of arctic Canada. The distribution of gravity observations in the Arctic is indicated on Fig. 2.

In 1950 a series of gravimeter measurements was made on the Barnes Icecap of Baffin Island in order to determine the ice thickness on the southeastern lobe of the ice cap (Littlewood, 1952, pp. 118–24). This study, which was carried out on the Arctic Institute's 1950 expedition, revealed interesting possibilities for the gravity method in the study of glaciology.

Seismology. By J. H. Hodgson

Although the first seismograph station in the Canadian Arctic was not installed until 1950, seismological studies of the area have been going on for some fifty years. Because the Canadian Arctic is bounded by European stations on the one side, and United States and Russian stations on the other, any moderate or large earthquakes in the area have been located through the routine operations of international seismology.[1] Actually the chief importance of the new Canadian station, which is at Resolute Bay, is in providing more accurate triangulation with any two stations farther south to locate epicentres in the northern hemisphere.

The new seismograph station was installed with this feature as a primary consideration. The original equipment consisted of a short-period Sprengnether vertical and two long-period Sprengnether horizontal seismographs, which provide an ideal arrangement for the recording of distant earthquakes. After a year's successful operation this equipment was increased and more extensive plans were made. Recently a long-period vertical, loaned by the Lamont Geological Laboratory of Columbia University, has been added to assist in the study of microseisms, and a three-component set of Willmore-Watt instruments may possibly be installed. These instruments will provide improved registration of local earthquakes as well as give additional data on the preliminary phases of distant shocks.

The original instruments were installed on a rock outcrop about 1,000 feet away from the meteorological station, and were connected by cables to the recording unit situated in the camp area (Bremner, 1952). The galvanometers and recorders were mounted on heavy timber cribbing, frozen into the permafrost, and were sheltered by a double-walled insulated building. This system of mounting proved so successful that experiments using permafrost as a base

[1]For a list of the principle arctic epicentres *see* Gutenberg and Richter (1949, p. 209).

for seismometers are now being carried out. A pier has been constructed on pipes driven into the permafrost, the pier being insulated carefully from the frozen ground. The new long-period vertical is at present operating with reasonable satisfaction on this base, and the proposed short-period instrument will be similarly installed.

The records are changed daily, and the readings are transmitted by radio to Ottawa, where they are relayed to the United States Coast and Geodetic Survey in Washington for use in epicentral location. Data are usually available within 24 hours, and the station has proved of considerable value in the international program of locating and studying earthquakes.

A few small local earthquakes have been recorded, but with only a single station in the area it has been impossible to locate their epicentres. Preliminary studies of microseisms have suggested a correlation of microseismic storms with storm centres over the North Atlantic Ocean, but no final conclusion has yet been reached. Finally, the recording of the surface wave L_g, at Resolute Bay, has led the Columbia group under M. Ewing (Oliver *et al.*, 1955) to conclude that the Arctic Archipelago is a part of the North American continental mass.

Arctic problems of the future. By C. S. Beals

The geophysical observations outlined above represent a beginning, in the Arctic, of the kind of systematic geophysical studies which have been carried out in more detail in southern Canada. For the most part, those branches of geophysics which are concerned with the solid earth do not make distinctions of climate or latitude. The Arctic is thus simply one more field to explore, with the proviso that transportation and living conditions are more difficult and expensive than in more southerly regions. This fact holds not only for the type of investigations already mentioned, but for commercial geophysics also. The various gold and base metal discoveries already made in areas like Yellowknife and Rankin Inlet make it practically certain that other discoveries will eventually be made farther north, and undoubtedly gravity and magnetic methods of geophysical prospecting will be used extensively. It is also known that some of the geology in the arctic islands is favourable for oil, and it will only be a matter of time before the area is fully explored with seismological methods.

Apart from the need to push geophysical exploration northward, there are a few geophysical problems specifically related to the Arctic which result from the rotation of the earth or from accidents of geography. One such problem is the location of the north magnetic pole and the fact that it appears to be moving slowly in a northerly direction. The methods used to locate the pole and to study its motion have been described by Madill (1948). Its present location is in northwestern Prince of Wales Island, and there is evidence that it has moved about 200 miles from a position in Boothia Peninsula, in slightly over a hundred years.

An interesting unsolved problem is the explanation of the position of the north magnetic pole and its counterpart in the southern hemisphere, relative to

the north and south poles of rotation. Modern theories of geomagnetism relate the major portion of the earth's field to its rotation, and it would seem reasonable to expect that the magnetic poles and the poles of rotation would coincide. It is well known, however, that the north magnetic pole is not at the north rotational pole and that a similar situation exists in the southern hemisphere. The fact that this is so constitutes a major problem in world magnetism, and one which concerns the earth as a whole and not merely the arctic regions. Nevertheless, it is a problem which is sharply pointed up by arctic observations, and one which arctic observers of geomagnetism must continue to study until a definite solution is found.

Another problem brought sharply to the fore by arctic observations is the motion of the north magnetic pole. In this connection, it should be pointed out that while most modern arctic observers are convinced that the pole is moving, the values of its position in 1831, given by Ross, and in 1904, by Amundsen, were based on much less adequate information than that of the present day. Modern scientists are grateful to Ross and Amundsen for providing good and reliable observations of great importance, but at the time their work was done, they lacked the modern means of transportation which have made it possible to surround the pole with observations, and so to fix its position with much greater exactness. It would appear, therefore, that a detailed and accurate study of the motion of the north magnetic pole is an arctic problem of the future which will certainly occupy an important place in geomagnetic studies during the next few decades. The cause of the pole's motion is beyond question bound up with the larger problem of the secular changes of the magnetic elements throughout the world, and its solution, if one is possible, will probably be on a world-wide basis. Nevertheless, no study of this matter could be complete without taking into account the arctic data on the motion of the north magnetic pole and on similar phenomena which may be observed in the antarctic regions.

There is still another intriguing problem related to the north magnetic pole which is of major interest to students of geomagnetism. If the earth, as a whole, is treated as a great magnet, the position of the magnetic axis may be derived by mathematical methods, utilizing magnetic observations over the whole surface of the globe. Such a calculation has been made, and the results show that the magnetic axis (which does not pass through the centre of the earth) cuts the earth's surface at a point in northwestern Greenland, some hundreds of miles from the observed position of the north magnetic pole as indicated by the convergence of magnetic meridians in the arctic regions. The fact that these two points do not coincide constitutes a most interesting problem. It is possible that the explanation may be found in the character of the earth's crust or of the earth's deeper layers under the arctic regions. If this is so, it seems likely that additional magnetic, seismic, and gravity observations in the arctic regions may eventually shed light on the problem. And though the magnitude of the program required to establish such a conclusion is beyond the scope of present-day transportation, these difficulties will no doubt be overcome as the Arctic becomes more developed.

Although the major part of the earth's magnetic field has its origin in the planet's deep interior, an important component has its origin in the electric currents of the high upper atmosphere. This atmospheric contribution to the geomagnetic field is strongly influenced by ultraviolet radiation and streams of charged particles from the sun. It is these influences which are largely, if not entirely, the cause of the short-term daily variations in the earth's magnetism, as well as of the violent and irregular variations known as magnetic storms. In any consideration of the position and the motion of the north magnetic pole these atmospheric phenomena must be taken into account, and it must be acknowledged that present information concerning them is far from complete. Another ten years of observation by the arctic observatories, completely covering at least one cycle of sunspot variation, will probably be required before the character of the short-term geomagnetic variations in the Arctic is completely understood.

The various magnetic problems mentioned above all require for their solution more accurate mapping of the earth's magnetic field in the Arctic than is now available. Even in southern Canada, where there is an extensive road and railway transportation network, the vastness of the country makes it difficult to establish as many ground magnetic stations as are really needed. The use of aircraft to transport ground observers, particularly in Canadian Shield areas, where water landings can be made readily, has considerably improved the situation, but even so, the number of ground stations is too few, and the areas of interpolation are too great to make possible the detailed accuracy in mapping which is desired. Airborne methods of magnetic observing are the obvious solution to this problem. Intensive development in this field has been going on both in Canada and the United States during the past few years, and some results of the United States effort, which included extensive mapping of the Arctic Ocean and adjacent areas, have been published (Hurwitz, 1953; Schonstedt and Irons, 1953). The Dominion Observatory has recently completed an airborne instrument for the simultaneous recording of all magnetic elements, and its first tests included approximately 5,000 miles of flying in the Canadian Arctic. The results of these flights have indicated that the major problems of airborne observational technique have been solved and that, as a consequence, significant progress in our knowledge of the earth's magnetic field in the Arctic is an immediate prospect.

The fact that the earth is not a true sphere, but a spheroid with an appreciable flattening at the poles, is of great interest to students of gravity. The actual shape is close to that of an ellipsoid of revolution with certain deviations in the vicinity of latitude 45° N. and S. One of the means of making precise determinations of the shape of the earth is by measurements of gravity. Ordinary geodetic measurements, for example of the number of miles in a degree of latitude at different distances from the pole, indicate that the flattening places the pole some 13 miles nearer the centre of the earth than is the equator. For very precise indications of the form of the geoid (the mathematical figure most nearly approaching mean sea level), gravity measures are necessary. Such observations make it possible to deduce, with greater

accuracy than by any other method, the various undulations of the geoid from the spheroid of reference. Undulations of this kind are produced by variations in the density of topographical features on the earth's surface and similar variations of density deep within the earth's crust, sometimes to a depth of several tens of kilometres. Deviations from the mean density of the crust are especially marked in mountainous regions and over ocean deeps, but they also occur elsewhere, and are important for understanding the equilibrium of the earth's crust, and for determining whether it is rising or sinking.

In order that studies of the earth's form should be complete, a very large amount of additional gravity data is required from the Arctic. Such observations are needed not only over the land areas but also, if possible, over the ocean, especially in the vicinity of the rotational pole. Unfortunately there seems to be little prospect of making gravity observations from the air, or of using present-day instruments with great success on ocean ice. There are certain new types of gravity meters being developed, however, which may eventually make it possible to take accurate gravity measurements on the ice of the Arctic Ocean. If, and when, this development takes place, the Arctic Ocean may actually be better mapped because of its covering of ice, than more southerly and apparently more accessible ocean regions.

Gravity observations are required not only for studying the form of the earth, but also for ascertaining the degree of isostatic equilibrium which prevails throughout the Arctic. Such studies have already been started in the region west of Hudson Bay and in the arctic islands, where there is evidence, in the form of raised beaches and altered shore lines, of considerable uplift since the last glacial age. Those gravity observations which have been made indicate that isostatic equilibrium has already been reached, and that further uplift is unlikely; but these observations are by no means complete, and it is hoped that they may be extended both in latitude and longitude during the next few years. It should be remembered, however, that while isostatic equilibrium in general indicates whether a given area of the earth's surface is rising or falling, it is not an infallible guide. Instances are known of drastic changes of level without obvious geophysical explanation. It is therefore essential that other types of measurement, such as tidal records and accurate levelling over land be made as well, if a sound knowledge of the earth's crust in the Arctic is to be gained.

In the field of seismology, not many problems have yet emerged that relate specifically to the Arctic. There is, however, a definite earthquake belt in the Arctic Ocean extending from the vicinity of Iceland to the mouth of the Lena river in Russia, but the shocks recorded there have not been intense. Earthquakes have also been recorded on the land area to the south of the Mackenzie River delta and in Baffin Bay (Gutenberg and Richter, 1949, pp. 363–78). The fact that these shocks have not been of great intensity, and that they have occurred in areas far from any major settlement has caused them to be of minor interest to seismologists who have still not solved all their problems relating to more seismically active areas farther south. Nevertheless, it may be expected that those arctic areas which have shown signs of activity will eventually be studied in more detail. It is possible that earthquake studies

carried out in these normally quiet areas may give more information about typical earth structure than those which occur in regions where the earth's crust is being subjected to major stresses of the kind which produce large earthquakes.

Another interesting problem of arctic seismology is the manner in which the surface waves of earthquakes are transmitted across the Arctic Ocean, which is shallower than the major oceans. Among the ways in which earthquake waves can be classified, we may here distinguish two main types: (a) those waves that are transmitted directly through the interior of the earth, and (b) those waves which, through their nature, are constrained to follow surface paths. Waves of type (a) have constituted, so far, the main object of seismological research. Their velocities are not dependent on their wave lengths and, in general, they move at higher velocities than type (b). Waves of type (b) are transmitted along the surface of the earth and their velocities are related to their wave lengths, the higher velocities usually being associated with longer wave lengths and *vice versa*. The relationship between velocity and wave length, however, is very different for continental and ocean paths, so that although the transmission of surface waves along continental paths and the floor of the Pacific Ocean has been studied in detail (Coulomb, 1952), a knowledge of their transmission across the shallower Arctic Ocean should prove interesting and valuable. At present, such a study is rendered difficult by the lack of seismograph stations both on the North American and Eurasian shores, although improvements in transportation, and the development of portable, yet accurate, seismological instruments should eventually make such studies practicable. When these improvements come about, a new approach will be possible to the study of surface waves as well as other problems of arctic seismology.

Both astronomy and geophysics have been involved in certain recent developments in the Arctic connected with meteors, meteorites, and meteorite craters. While some of the solid bodies which enter the earth's atmosphere from outside space reach the ground relatively intact, the vast majority are disintegrated at considerable heights by the intense heat generated by friction with the air. One of the products of such disintegration is meteoric dust, which consists mainly of small spherical particles, probably formed of molten material swept from the hot surfaces of meteors as they move through the atmosphere.[1] It is clearly important to distinguish between meteoric particles and those of terrestrial origin. The large ice- and snow-covered areas of the Arctic are very well suited to this purpose, and it is hoped that the collection and analysis of meteoric dust from snow surfaces may take an important place in the work of the increasingly numerous arctic stations.

Of the meteoric bodies large enough to reach the ground, only the larger ones are normally found, since most of the smaller meteorites are either buried in the soil or have become indistinguishable from their surroundings through weathering. An exception is found in those small meteorites which fall on ice

[1]For a brief description of methods of collecting and analysing meteoric dust *see* Thomson (1953).

surfaces, and are clearly visible because of their darker colouring. A number of interesting meteorites have already been detected in this way, and it seems likely that when more people are living or travelling in the Arctic, an increasing number may come to light. Certainly any piece of rock with no obvious local origin, found on an ice surface, should be examined carefully for a possible meteoric origin.

Another arctic connection with meteoric phenomena is the great Ungava crater,[1] northwest of Fort Chimo, which is generally believed to be of meteoric origin (Meen, 1950; Meen and Stewart, 1952). If it is a meteoric crater, it is the largest so far observed on earth, being between two and three miles in diameter. It is now known to be preglacial in age although recent in geological time, and has been little altered by erosion. These factors have given it unusual scientific importance, and it is being studied from several points of view, one of which is a mathematical investigation of the physical mechanism responsible for explosion crater formation. One reason for the great interest in large craters of this kind is their possible relationship with craters on the surface of the moon, which are also believed to have a meteoric origin. Because of its size, the Ungava crater affords by far the best opportunity for comparing terrestrial and lunar craters. It seems likely that at one time the number of craters on the earth and moon was comparable, but that erosion and deposition obliterated almost all traces of the really ancient terrestrial craters, leaving only a few of relatively recent age. Nevertheless, it seems probable that if sufficiently detailed studies were made in remote parts of the Canadian Shield, which has remained free of major geological changes for a very long time, some indication of ancient craters might be found. One circular feature, which may possibly be such a crater, has been discovered in Algonquin Park. But it is also true that on several arctic islands, for example, Ellef Ringnes, Axel Heiberg, and Melville, a number of circular features which were thought at first to have been caused by meteors, later appeared to be due to other causes. In spite of this it is possible that the Arctic may contain some of the most important clues necessary for solving the intriguing puzzle of lunar craters and their relationship to terrestrial phenomena.

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THE IONOSPHERE OVER NORTHERN CANADA

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COMMUNICATION problems in northern Canada, as elsewhere, are primarily a matter of cost. In densely populated areas the great volume of communications justifies expenditures for telephone, telegraph, and multi-channel radio-relay networks, supplemented by the broadcast facilities of AM and FM radio and of television. In the north the present population is too small and widely scattered and the potential volume of communications too little to justify the expense of elaborate facilities. The most economical method of providing fast communication for the area is by short-wave radio via sky-wave transmission, as the installation and the electrical power required are relatively small. More specifically, short-wave radio means propagation via the ionosphere, an electrified reflecting layer between 60 and 200 miles above the earth's surface, on radio frequencies between 3 and 30 megacycles. Today, most of the small northern settlements of Canada possess short-wave radio equipment.

Short-wave radio systems, although reliable most of the time, suffer from occasional failures owing to disturbances in the ionosphere. Unfortunately, the ionosphere over a great part of northern and central Canada is often more disturbed than it is over most other regions of the earth because the earth's magnetic field approaches the vertical, allowing charged particles from the sun to penetrate more deeply into the earth's atmosphere over these regions. The auroral, or northern light zone, coincides with the southerly two-thirds of this region. Although auroral and magnetic phenomena are often associated with ionospheric radio disturbances the aurora is rarer farther north, but the ionosphere is still very much disturbed. Short-wave radio therefore suffers from interruptions throughout the auroral zone and into the polar area.

The pressing economic need to make the best possible use of short-wave radio in Canada has led to intensive observation and study of the ionosphere, and has stimulated research into other phases of the physics of the upper atmosphere. To study ionospheric changes, the Telecommunications Division of the Department of Transport, in cooperation with the Radio Physics Laboratory of the Defence Research Board, has established eight ionospheric recording observatories.[1] Four of these, at St. John's, Newfoundland, Ottawa,

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[1]Another ionospheric station was set up by the Carnegie Corporation at Clyde in 1943 and was taken over by the Department of Transport in 1945; it has now been discontinued.

Winnipeg, and Prince Rupert, skirted the southern part of the auroral zone from east to west. Stations at Churchill and Fort Chimo were near the line of maximum auroral occurrence, and those at Baker Lake and Resolute Bay extended the line of observations from Winnipeg, in the south, to a point north of the magnetic pole. For several years measurements of the height and electrical density of the three main levels of the ionosphere have been continuously recorded by means of variable frequency radar at all of these stations. In 1954 the stations at St. John's, Fort Chimo, and Prince Rupert were discontinued.

From observations already obtained it is possible to predict the average height and electrical density of the ionosphere for a given time of day and season of the year, and therefore to select the best radio frequencies for specific short-wave paths over most of Canada. Studies of ionospheric disturbance have also shown that interruptions to short-wave radio are more frequent in the spring and fall than in the winter and summer. They are also more frequent in years of high sunspot activity, such as 1947–9, than they are in years of minimum activity, such as 1954–5. Some success has now been achieved in forecasting ionospheric disturbances as much as a month in advance.

The radio-noise level of northern Canada is low compared with that of southern Canada, which in turn is lower than that of tropical regions. Weaker radio signals can be detected and used in the north than elsewhere, so that relatively little transmitter power is required. One reason for the absence of noise is that intense radio energy from the numerous tropical thunderstorms diminishes rapidly at a distance of 4,000 miles. Noise from local thunderstorms, and from machinery and radio equipment is also low in the north, even during the summer, when the general noise level is higher.

This relative lack of noise and the improved methods for selecting radio frequencies, have made short-wave communications in northern Canada reliable about ninety per cent of the time. Unfortunately, the failures may occur in periods of one to three days at a time. This is not important for ordinary traffic since delays of this order are infrequent, but for urgent traffic, such as reports on sickness or weather, it is a serious handicap. Any short-wave circuit which is less dependable than ninety per cent should be checked for the condition of the equipment and the suitability of the radio frequency. If the frequency is too high for a given path the receiving station will be within the "skip-distance" of the sending station. If the frequency is much below the correct value its energy may be absorbed in the lower atmosphere instead of being reflected. Advice on the best radio frequencies and times of day for specific paths can be obtained from the Radio Physics Laboratory of the Defence Research Board at Ottawa.

Ionospheric research has also opened up a wide range of theoretical and experimental problems, particularly in high magnetic latitudes. The science of the physics of the upper atmosphere, of which the ionosphere is a part, is being given increasing attention in Canada and is bringing closer cooperation between theoretical and experimental physicists and radio engineers. Intensive research on the spectra, luminosity, height, and electron density of the aurora

is being made at the Physics Department of the University of Saskatchewan. The correlation between auroral, ionospheric, and magnetic disturbances is also being investigated at this university in cooperation with the Radio Physics Laboratory in Ottawa. It is hoped that a spectrograph of very high dispersion designed by the Radio Physics Laboratory for use at Churchill, will give much more detailed auroral spectra than have previously been obtained, and will enable more exact determinations to be made of the constitution, energy changes, and temperatures at different levels in the upper atmosphere. Parallel with these auroral measurements, a laboratory study is being made of artificial aurora produced in discharge tubes.

A joint project of the Dominion Observatory and the Radio Engineering Division of the National Research Council is yielding interesting information on meteor showers and the ionization produced by meteors in the lower atmosphere. Investigations of aurora and other ionization processes of the upper atmosphere are being extended northward and should give further information about one of the most complex regions of the ionosphere. It is hoped that the formation of the advisory committee on radio science by the National Research Council will stimulate further interest in the ionosphere.

Three main problems of the ionosphere over northern Canada, as elsewhere, remain unsolved.[1] Each is complex, and requires subsidiary investigations employing radar, spectroscopy, and magnetic and radio-signal strength recording. First is the problem of forecasting storm conditions in the ionosphere in order to improve radio communications. While the complete solution of this problem is not urgent in low latitudes, it is very important for Canada. Second, the nature of the extreme ultra-violet radiation of the sun is not sufficiently understood, and should be thoroughly investigated in the ionosphere and other parts of the upper atmosphere. Improved techniques of rocket measurements made by United States engineers should be very helpful in this regard, and may even bring our knowledge of extreme ultra-violet radiations in the upper atmosphere near completion. Third is the puzzling problem of winds and tidal effects in the upper atmosphere. In several countries radar techniques for measuring winds in the ionosphere have yielded challenging results. Continued investigations will undoubtedly throw increasing light on this interesting question.

[1]For a discussion of subsidiary problems *see* Mitra, S.K. 1952. 'The upper atmosphere'. Calcutta: The Asiatic Society, 713 pp.

GEODETIC INVESTIGATIONS IN THE CANADIAN ARCTIC

J. E. R. Ross*

THE first step in the scientific investigation of an undeveloped district is accurate mapping. Where geodetic surveys, whether by astronomy, triangulation, or by shoran trilateration, are used to establish the necessary control for mapping, the data obtained are also of value in computing deflections of the vertical, in determining the undulations of the geoid and the thickness of the earth's crust, and finally, in deriving the dimensions of the spheroid of revolution which conforms most closely to the geoid.

Over the last one hundred years, geodesists in different parts of the world have derived the mathematical dimensions of five spheroids which are in reasonably close agreement. The ultimate aim of the research is to derive a geoid and a spheroid from data which are world-wide in coverage, and therefore free from the effects of local anomalies. In the Canadian Arctic and Subarctic methods of survey based on geodetic astronomy and shoran trilateration have already been used. In the foreseeable future, geodetic triangulation and precise levelling will also be used and should advance geophysical research in these regions.

The Geodetic Survey started its arctic work in 1935, when C. H. Ney determined the astronomical positions at some of the points of call of the Hudson's Bay Company's R.M.S. *Nascopie*. In 1942 the northern operations of the Geodetic Survey were expanded, and between that year and 1950, 300 astronomical stations were established for control for mapping from air photographs north of the tree-line. About 200 of these were on the mainland, the remainder on the more southerly arctic islands.

The determinations were made by Ball's method, using a precision theodolite set at a vertical angle of 45 degrees or 60 degrees. A minimum of four stars was observed in each quadrant, and the time recorded by stop watch or electric chronograph. In favourable weather a party could complete four to eight stations a month. Occasionally prolonged periods of overcast skies prevented astronomical work. During such periods hourly magnetic observations were taken in the daytime, and botanical and zoological collections were made by some of the parties.

During the past few years the shoran electronic method of position fixation has superseded the astronomic method in most parts of northern Canada. This new system of survey permits the extension of ground control for mapping and charting into remote areas in a much shorter time than would be required by

*Dominion Geodesist.

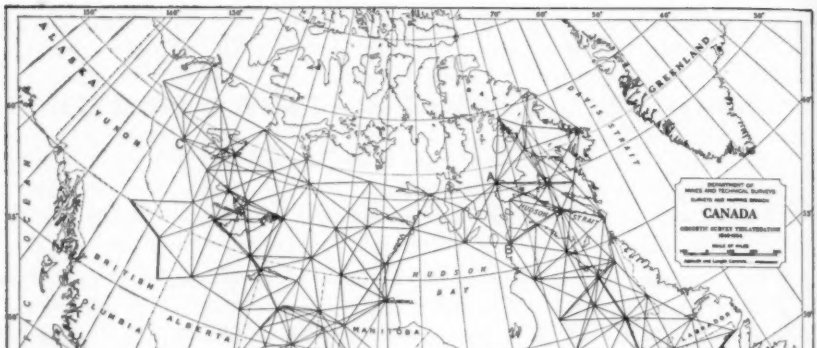

Fig. 1. Shoran trilateration in northern Canada.

the use of the conventional type of triangulation. Shoran trilateration consists of measuring electronically three sides of large triangles joined to form an over-lapping series of geometrical figures. The triangles are extended initially from a known base line joining two previously determined geodetic triangulation stations. By the shoran method distances between points up to 400 miles apart may be determined with an accuracy of 20 to 50 feet.

Through the cooperation of the Royal Canadian Air Force, airborne electronic equipment is used in conjunction with ground sets mounted temporarily at the terminal stations of the line being measured. The aircraft flies back and forth across the line near its central point at uniform speed and height, emitting short radio pulses which are sent to the terminal ground stations and then returned on a different frequency after a very short fixed delay. The elapsed time between dispatch and reception is recorded by mileage dials, which together with other dials are photographed at intervals of three seconds.

Immediately after the return of an aircraft from a line-crossing mission, Geodetic Survey personnel at the operational base camp receive the photographic records of instrument readings and make the necessary mathematical reductions. Corrections to each length obtained are made for delay of signals at the ground stations, height of aircraft and terminal stations above sea level, slope, humidity, temperature, and barometric pressure. Sixteen independent length determinations are made of all lines on two separate days in groups of eight each to ensure a change of atmospheric conditions and to check equipment. Further mathematical checks are made where possible. When field

analyses are satisfactory, the ground electronic equipment, consisting of transponders, radio communication sets, power supply units, and radar masts, are dismantled and moved forward to new stations in the network. The final least squares adjustment of the network as a whole, and the computation of geographical positions, azimuths, and lengths are made by the Geodetic Survey in Ottawa.

Since 1949 the Canadian shoran net has been extended from the vicinity of the 49th parallel in Manitoba, north and northwestward as far as the arctic coast in the Mackenzie River area. Beginning some 200 miles to the south of the northern point reached in 1951, a branch was continued eastward 1,000 miles to the western limits of Hudson Strait by the end of 1952. During 1953 the network was extended northward across Hudson Strait to the central part of Baffin Island, and a junction was made near the western end of Hudson Strait with the existing shoran net. This junction completed a 5,600-mile closed loop of survey control. The southern part comprised a 2,000-mile arc of conventional triangulation; the remainder consisted of shoran trilateration. The closure error in geographical position was equivalent to 400 feet. If it is assumed that the entire error was accumulated in the 3,600-mile shoran component of the loop, the ratio of closing error to axial length is only 1/47,000, equivalent to 1⅓ inches in one mile. In 1954 the shoran work was continued in Labrador, more stations being established within the basic framework.

Since its inception in 1949, shoran trilateration had been extended by the end of the 1954 season over 1,900,000 square miles of the Canadian north, a large part being north of the 60th parallel. In all, 86 stations involving 325 measured lines ranging from 16 to 366.8 miles in length are comprised in the network.

Problems and future work

One of the major undertakings for Canadian geodesists will be the extension of primary triangulation arcs from the more southerly areas into the Arctic, so that connections may be made with the northerly sections of the shoran network. This will greatly strengthen mathematically the existing shoran framework in addition to providing a dense pattern of control points in specified areas between the shoran stations.

Geodesists foresee interconnection of the geodetic triangulation networks of Europe, Asia, and Africa with those of North America. This may conceivably be achieved by shoran trilateration connections across Bering Strait, or between the Canadian Arctic shoran net and the triangulation systems of Greenland, Iceland, and the British Isles. A project of this nature would make possible the establishment of a "world geodetic datum" to which all triangulation and trilateration surveys on land masses within electronic measurement distance of the interconnected continents could be referred.

One great advantage of a "world geodetic datum" would be the coordination of data from isostatic studies in various countries. Deflections of the vertical determined in the Canadian Arctic by geodetic methods could be

accurately related to values observed in England or Africa. In this way, the studies of the geoidal contours and the determination of the best-fitting spheroid of revolution would be greatly advanced.

Gravity observations would be an important part of a planned world program for the study of geophysical problems. If gravity observations were available for all parts of the world on both land and water, an extensive mathematical reduction by Stokes's Theorem would permit accurate calculation of the undulations of the geoid and the extent of the flattening of the earth towards the poles. But from gravity observations alone it is not possible to compute the lengths of the major and minor axes of the earth. At the present stage of development of the science, a combination of astronomy and geodesy constitutes the most effective and practical approach to the determinations both of deflections of the vertical and of the dimensions of the spheroid of revolution which most closely conforms to the size and shape of the earth. The usefulness of the two methods of approach to the study of variations in densities of the earth's crust is suggested by recent findings in the Great Bear Lake region, where the geodetic shoran network has indicated large anomalies in the general pattern of deviations of the vertical. An intensive gravity survey in the same area might provide technical data of both scientific and economic value.

Geodetic investigations of changes in mean sea level should be extended to the Arctic. With the ameliorating climatic conditions of recent years in the north the weight of the glacial remnants has been reduced and increased amounts of water from melting ice have found their way into the sea. The resulting diminution of pressure in several areas may be expected to cause isostatic readjustments of the earth's crust, either suddenly, accompanied by earthquakes, or very slowly in the form of a gradual tilting. Such a tilting has been definitely indicated over a period of years by geodetic levelling in the Great Lakes region both north and south of the international boundary. The alterations in mean sea level can best be measured by repeated levelling over selected lines at intervals of about twenty years. Changes indicated by coastal tide-gauge stations and permanent bench marks, situated at intervals along the lines, will also give a measure of the crustal tilting.

The basic problems of geodesy in the Canadian Arctic are similar to those in other parts of the country, but the amount of geodetic work already done in the north is small compared with that in the south, and increased knowledge of the north would be of great benefit in all geophysical research.

OCEANOGRAPHIC PROBLEMS OF THE ARCTIC OCEAN

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THE central problem in oceanography is to understand the movements of the water. This is true whether a study is primarily concerned with the physics, the chemistry, or the biology of the sea. Although the oceanographer deals with much slower movements than the meteorologist, he is beset by many of the same sorts of questions. To both, the motions observed occur within a relatively thin fluid envelope on a rotating earth. To both, the scale of the motions of interest covers a very wide range and both periodic and non-periodic motions are involved. Over most of the oceans the winds and the currents interact in many subtle ways, and it is often difficult to distinguish between cause and effect.

While it has become clear that ocean currents derive much of their energy from the winds, it is also evident that heating and cooling play a significant role. Some currents are almost pure wind currents; others are maintained largely because of regional differences in density. In most currents both causes are at work, and it is usually extremely difficult to establish their relative importance. However, much of the theoretical work in oceanography has been in connection with wind currents, as theories that can help to explain the characteristics of currents that are partly wind-driven and partly density-driven are beset by great mathematical difficulties. In the past, at any rate, theoretical studies have been most helpful in physical oceanography after the physical characteristics of the situation could be described in a reliable manner. In oceanography theory alone has seldom led to advances.

The exploratory stage of arctic oceanography is now drawing to a close. In very general terms the physical, biological, and geological characteristics of the area can be described as the result of a number of arduous and costly expeditions. To an oceanographer the Arctic Ocean is no longer an unknown sea. Ice-free waters that are just as cold are available to him elsewhere, and to be able to reach higher latitudes does not in itself hold promise of advancing his primary problems. But the arctic region[1] can make an important contribution to physical oceanography. As Worthington (1953) has shown, the

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[1]In this paper Dr. Iselin is concerned with the Arctic Ocean basin only, not with the waters of the arctic islands, Canadian coastal waters, Baffin Bay, or Hudson Bay. *Ed.*

Arctic Ocean is the only sea in which circulation occurs down to very considerable depths in the absence of any significant supply of energy from the local winds.

The circulation of the Arctic Ocean therefore presents a unique problem in physical oceanography. The winds can move the ice to some degree, as several expeditions have shown, but the frictional effect of the ice on the water must be minor compared with the regional differences of density, level for level, between the truly arctic waters and those of the Norwegian Sea. Moreover, recent knowledge of the topography of the Arctic Ocean Basin shows that the problem is even more interesting than it was previously thought to be. Only five years ago, when Sverdrup (1950) reviewed our knowledge, or rather lack of knowledge, concerning the physical oceanography of the arctic basin, he could not have realized that it was cut in half by a pronounced ridge. Worthington (1953) later suspected this, but it is only since the results of the Soviet expeditions have become known that it was certain bottom topography must profoundly influence the deep circulation (Webster, 1954).

Thus, a significant challenge faces students of oceanic circulation problems: Here is a sizable, deep basin covered with ice, one half of which is connected directly to another deep basin—the Norwegian Sea, which is largely ice-free—and the other half of which is to some extent isolated by the newly discovered Lomonosov Range. While the velocities of the currents under the ice may be weak, Worthington's (1953) calculations indicate that considerable transports are involved, even in the remote part of the basin. How can the study of the main problem that this area presents be advanced, what sorts of facilities are required, and what factors peculiar to the Arctic are favourable or unfavourable? In comparison with other large-scale aspects of the circulation problem the situation on the whole appears to be favourable, and undoubtedly many other interesting oceanographical phenomena will be encountered in the course of studies of the arctic circulation.

The primary assumption in deep sea oceanography, namely, that the flow is relatively steady so that a balance of forces exists, is probably most fully justified in the Arctic Ocean because the disturbing effects of the local winds are mostly eliminated. Thus, in the Arctic the necessity for simultaneous observations is largely removed and observed and computed currents can be compared with considerable expectation of agreement, especially since the disturbing effects of internal waves are probably largely eliminated, even though the collection of a deep network of temperature and salinity observations may have required a considerable period of time. In addition, even though the currents are relatively weak, it should be easier to obtain accurate measurements of the change of velocity with depth working from the ice, a very favourable platform for current measurements, than is ever possible from a ship. At lower latitudes an oceanographer has to study currents that he is virtually unable to measure with the desirable accuracy. Since the currents in the Arctic Ocean are probably slow, broad, and relatively steady, a rather open network of points of observation should suffice. A satisfactory analysis

could emerge even though the points of observation were separated by as much as 100 miles on the average. As oceanographers have learned during the last few years, a considerably closer network of nearly simultaneous observations is essential in seas that are exposed to the winds.

Although in the Arctic a comparatively small number of points of observation may well suffice, the oceanographer is faced with a serious, but not necessarily expensive, transportation problem. An aircraft is considerably cheaper to operate per mile than a sea-going vessel, but the difficulty at present seems to be that nobody has designed an aircraft specifically for arctic oceanography. An aeronautical engineer with this purpose in view would certainly be facing a limited market, but the fact remains that reliable and economical transportation is the chief requirement of arctic oceanography. All other aspects of a productive observational program could be solved fairly quickly on the basis of existing knowledge and experience. Most of the readily available instrumentation of oceanography has been designed to withstand the normal conditions at sea, a heaving ship and a ready supply of power, rather than to operate in the ice and to meet the requirements of an airlift. But to devise oceanographic instruments in miniature and otherwise to improve them for use in the Arctic could be quickly achieved, the bottle-neck for the time-being is the transportation. To set up camps on the ice and to depend on the slow drift of the ice to gain coverage, as has usually been done in the past, does not seem the most efficient way to attack the majority of arctic oceanographic problems. The requirement is to move two trained observers and perhaps 1,000 pounds of equipment to a network of points separated by about 100 miles and to give the men a few hours at each station to make their observations. Until such transportation is available most oceanographers will find it more profitable to study problems for which advances can still be made from ships, and most of the gains in arctic oceanography will probably continue to come as a by-product of expeditions whose objectives are not limited to the classical problems of oceanography.

During the summer season many interesting studies can of course be carried out along the shallow margins of the Arctic Ocean, even from quite small craft. From the ecological standpoint especially, such expeditions will continue to be profitable for many years to come. Another possible approach for both summer and winter work would be to design radio-telemetering instruments that could be air-dropped into open leads to secure observations from the deeper parts of the Arctic Ocean, but until the problem of precise aerial navigation is solved, landing on the ice with the oceanographic instruments will be a sounder method. A reliable geographical fix is especially critical in the case of physical measurements. Nor could a submarine at present really solve this need for accurate navigation, except in so far as it were practicable to surface in open leads. Where am I? and just where is my instrument relative to my position? become increasingly important questions as oceanography emerges from the exploratory stage. These are difficult enough questions to answer with precision from a ship, even in areas where

the latest navigational techniques are available. Thus, although mobility is important to an oceanographer, he must also be able to fix his location at frequent intervals.

While the difficulties of transportation may seem considerable today, the Arctic Ocean has at least two great attractions to an oceanographer: It is not nearly as large as, say, the Pacific Ocean, and the ice provides a nearly ideal platform from which to work.

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TIDAL DATA IN THE NORTH AMERICAN ARCTIC

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KNOWLEDGE of tidal conditions in North American arctic waters is meagre when the vast area of these waters and the great extent of the coastal shorelines are considered. Tidal observations are difficult to obtain due to the prevalence of ice, scarcity of inhabited areas, and the inaccessibility of the region. Available data are inadequate, sometimes of dubious quality, and frequently insufficiently distributed to permit a proper study of the tidal regime. In many areas the range of the tide is small and therefore long periods of observations are necessary to separate comparatively large variations due to meteorological conditions from true tidal fluctuations.

Prior to 1945 the tide had been observed at only a few places along the Arctic Ocean coast of Alaska and Canada. In the last ten years observations have been obtained at about twenty additional places. These additional observations are sufficient to establish that the range of tide along the arctic coast of Alaska, east of Cape Lisburne, is only about one-half foot. The limited durations of the observations do not provide data for long-period investigations of sea level variation. Tidal harmonic constants have been derived for Cape Columbia and Cape Sheridan, Ellesmere Island. They are based on a 29-day series in 1908 and 220 days in 1905 to 1908 respectively.

Tidal observations in the numerous channels between the islands of the Canadian Arctic ordinarily supply local information only and inferences on tidal conditions in nearby channels would in general be unreliable. The observations at Winter Harbour, Port Kennedy, Port Leopold, Beechey Island, Penny Strait, and Discovery Harbour are of sufficient length for harmonic analysis and the tidal constants necessary for predictions are available. Shorter periods of tidal observations are being obtained at an increasing number of other stations in the area, particularly the far northern weather stations.

In Hudson Bay and Hudson Strait there is a reasonable coverage of tidal observations, except for the southern and eastern parts of the bay. More stations are still required, particularly in Hudson Strait where the exceptionally large range of the tide makes a greater than normal density of tidal stations necessary. Harmonic constants are available for Churchill and Diana Bay, and sufficient data have been obtained for harmonic analysis from Port Nelson, Rankin Inlet, Chesterfield Inlet, Coral Harbour, Koksoak River, Leaf Basin, and Leaf Bay.

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